

CRANFIELD UNIVERSITY

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Study of Optimisation Strategies for Aircraft Structural Design

School of Applied Sciences

MSc by research
Academic Year: 2011 - 2012

Supervisor: Dr. Jörn Mehnen
Supervisor: Prof. Ashutosh Tiwari
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the degree of Master

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ABSTRACT

Optimisation plays an important role in structural design. Structural design optimisation is not only a matter of weight reduction of the structure; it can be used to optimise any type of objectives. In engineering practise, it is also common to maximise performance parameters such as the maximum load capacity and the fatigue life of a structure. Besides, the structural design in modern commercial aircrafts inevitably involves considerations such as aerodynamic performance and system requirements. Therefore the optimisation of structural design usually has various disciplines to be taken account of. Hence, the single objective, multi-objective and multi-disciplinary optimisation problems are very important in engineering practise.

The aims of this research project are to classify and summarise typical optimisation applications and their objectives and constraints in aircraft structural design to help engineers to solve their optimisation problems. In addition, this study aims to develop a systematic framework and recommendations for approaches to various problems in this domain to inspire engineers to solve their optimisation problems.

To achieve this objective, a literature review is carried out, focussing on four aspects: Modelling of CAD structures, Finite element analysis of structures, Structural Optimisation and Mathematical Optimisation. In addition, a survey was undertaken with 15 experts with different backgrounds from Europe and other countries. Meanwhile, three experts in aerospace industry are called for an interview.

This thesis also presents the engineering applications in various aircraft components. The fuselage component multi-disciplinary (structural, acoustics and thermal) optimisation is discussed. In terms of the wing component, the space unit of the wing box is defined for optimisation, and different constraints for different parts are summarised. In addition, brief introduction of other component optimisations are introduced.

This thesis also presents the development of a systematic framework for the aircraft structural optimisation approaches. The general approach, and the DOE & Algorithmic approach are defined and adopted in the framework. A framework chart is illustrated to help engineers to initialise their problems in the initial phase and cope with them following the workflow of the framework chart. In order to highlight useful and practical suggestions for the engineers and designers, recommendations are presented in this thesis.

Case studies are carried out to demonstrate and validate the function of the framework. There are three case studies in this thesis, and all of them are from industries. The first one is a door hinge with single-objective topology optimisation problem. The second one is a crank with multi-objective shape optimisation problem. And the third one is a landing gear torsion link with a combined (topology, shape and sizing) optimisation problem. HYPERWORKS is adopted to conduct the optimisation, which includes built-in parameterised tools to generate the mesh solver, carry out the finite element analysis, and optimise the design with various algorithms.

This study indicates that the optimisation is not always applicable in every phase of the design. The preliminary phase is crucial for the entire optimisation. The optimisation framework developed in this study can be systematically applied in aircraft structural design. Engineers should learn about the DOE and algorithmic approach in order to solve the multi-objective or multi-disciplinary problem, and the approach framework developed in this study could provide a good guideline.

Keywords:

Aircraft, Structural, Design, Optimisation, Strategies, Single objective, Mono-objective, Multi-objective, Multi-disciplinary, constraint, workflow

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LIST OF ABBREVIATIONS

API	Application programming Interface
COMAC	Commercial Aircraft Corporation of China, Ltd
CAD	Computer-aided design
CU	Cranfield University
DOE	Design of Experiment
DCGA	Diversity control genetic algorithm
EA	Evolutionary algorithm
FEA	Finite element analysis
FEM	Finite element method
GA	Genetic algorithms
GII	Graphics interactive interface
LHS	Latin hypercube sampling
MDO	Multi-disciplinary optimisation
MOO	Multi-objective optimisation
MOEAs	Multi-objective evolutionary algorithms

1 INTRODUCTION

1.1 Background

The aviation market is developing very fast nowadays and has a promising future in the next few decades, especially in emerging countries such as China, India, Brazil and Russia. For those countries who have gained great success in the economic development, they are eager to enhance the technology capacity in order to improve their competitiveness.

The aerospace industry is a strategic sector which is high-tech and high value-added. Therefore the development of the aircraft industry is regarded as a catalyst to boost the competitiveness.

1.1.1 The Collaboration Company

COMAC, stands for Commercial Aircraft Corporation of China, is the sponsor of this study. It is a company with a commitment to designing and manufacture of the first Chinese Jet: C919 (which stands for COMAC919).

To meet various operating requirements and market demands from the airline clients, the C919 will be designated to have different configurations. There are 168 seats in all economy class configurations, and 156 seats in the hybrid configuration. The range for the initial model will be 4,075km, with a potential range of 5,555km for the next generation model. The life-cycle of C919 is 90,000 flying hours/30 calendar years. Such designs may satisfy the operating demands for separate routes.

Although COMAC was only established in 2008, huge progresses have been made. COMAC has finished the conceptual design of C919, and the detail design will be expected to complete soon. COMAC has obtained 270 orders of C919 at present.

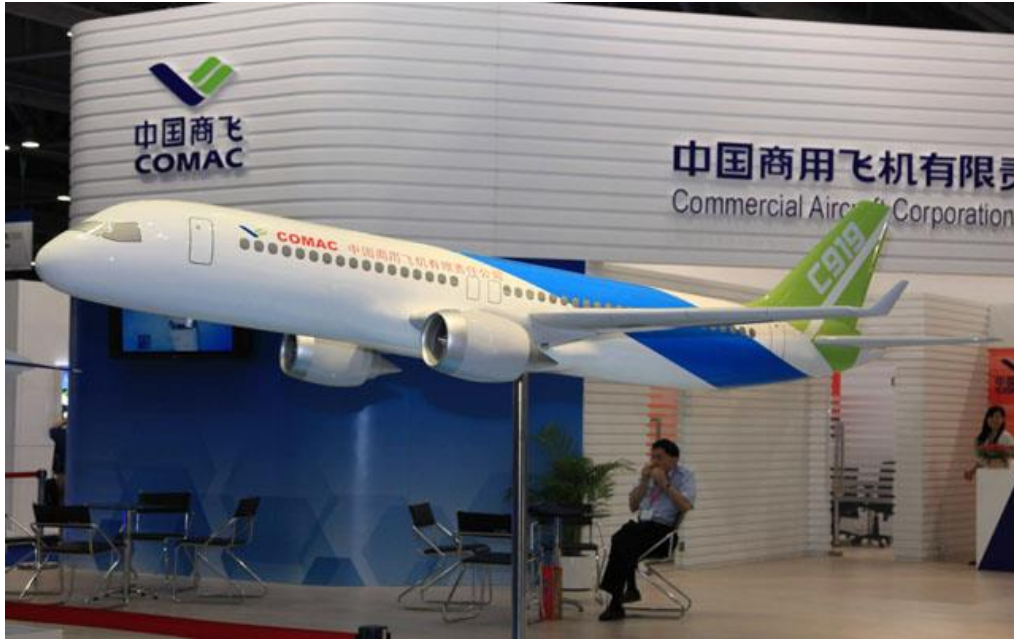


Figure 1 The demonstration model of C919, from
<http://www.ainonline.com/aviation-news/ain-air-transport-perspective/2010-01-25/chinas-engine-aspirations-taking-shape>

1.2 Research Motivation

It would be extremely difficult to develop an aircraft industry if there are not enough engineers and experts with sufficient experience and professional knowledge in aircraft structural design. Optimisation plays an important role in aircraft structural design. At present engineering designs in the Chinese aerospace industry are still optimised commonly through a manual iterative process in which the engineer evaluates several possible designs and selects the optimum considering certain kinds of criteria, such as maximum stress and weight. For inexperienced structural design engineers, since little could be found in the literature about the systematic classifications of optimisation applications and framework of optimisation approaches, they have to spend a lot of time with learning and deciding on optimisation models, parameters, constraints etc. and how to combine simulation software best with the various optimisation algorithms.

Aircraft structure is a complicated combination of several components with different functions, requirements and specifications. Hence, it is necessary to summarise typical objectives (or objective functions) and constraints (or constraint functions) in the airframe main components such as fuselage, wing, the landing gear and pylon respectively, based on the published or internal paper, report, questionnaire and interview.

Consequently the work of engineers could become more efficient if they had practical guidelines that provided recommendations for a more systematic approach to optimisation of aerospace structures. This thesis addresses this general problem while focussing on applications of typical design tools such as CAD and FEA software.

For COMAC (Commercial Aircraft Corporation of China, the sponsor of this study), this study is particularly useful. As many structural design engineers in COMAC lack of the experience of optimisation, they need a list of optimisation applications which have been settled to inspire them which parts could be optimised and which disciplines should be considered.

Moreover, recommendations are necessary to guide them how to define objectives, identify constraints, generate workflows, choose algorithm and carry out good optimisation efficiently.

1.3 Project Scope

The aircraft industry can be divided into 2 types: Commercial aircraft and military aircraft. As introduced in the background section, the sponsor of this study is a company focuses on commercial aircraft industry, therefore this study targets at the commercial aircraft industry only, while the military aircraft is out of scope.

The engine works under extremely high temperature conditions, it has its unique material and specification. None of the commercial aircraft manufacturer around the world makes engine. Considering the target of this study is commercial aircraft industry, this project does not involve the engine.

In the broad sense, there are many kinds of structure in the commercial aircraft, such as airframe structures, system structures and interior structures. The airframe structures consist of wing, fuselage and other components. The system structures are the firmware of various systems, such as the avionics system. The interior structures are panels or plates for decoration of the cabin. In general practice, only the airframe structures are considered to be in scope when it comes to aircraft structural optimisation.

Although the composite material is gradually popular in aircraft structures, it differs from the metal structures design and has unique optimisation approaches. Considering the timescale of this study, it is not discussed in this thesis. However, the composite structural optimisation will be studied in the future work.

Hence, this research project concentrates on the following areas:

- a) Commercial aircraft industry
- b) Airframe structures

And the following points are deemed to be out of the scope of this research project:

- a) Other industries except aircraft
- b) Military aircraft
- c) Engine
- d) System structures
- e) Interior structures
- f) Composite structures

1.4 Aims and Objectives

The aims of this research project are to:

- a) classify and summarise typical optimisation applications and their objectives and constraints in aircraft structural design to help engineers identify their optimisation problems;
- b) develop a systematic framework and recommendations for approaches to various problems in this domain to inspire engineers to solve their optimisation problems.

The objectives of this research are to:

- a) Classify popular optimisation applications in airframe design;
- b) Summarise typical objectives and constraints in those structural optimisation problems;
- c) Develop a systematic framework for solving single objective, multi-objective or multi-disciplinary problems with off-the-shelf optimisation tools;
- d) Develop recommendations for how to carry out the optimisation effectively and efficiently.

1.5 Thesis Structure

There are 8 chapters in this thesis. The first chapter provides an overall introduction to the research topic. Chapter 2 presents a comprehensive literature review which is conducted to gain foundations of knowledge. Chapter 3 defines the adopted research methodology. Chapter 4 introduces the questionnaire and interview, and analyses the responses. Chapter 5 presents the development of the framework of approaches for aircraft structural design optimisation. Chapter 6 shows three case studies, demonstrates how to optimise the parts of aircraft using the framework developed in this study. Chapter 7 gives discussions and recommendations on when and how to use optimisation. Chapter 8 summarises this study and presents the conclusions, as well as the future work.

1.6 Summary

This chapter explains the background and motivation of this research, and introduces the scope, aims and objectives. Optimisation plays an important role in aircraft structural design. However the aircraft engineering designs nowadays in China are still optimised commonly through a manual iterative process in which the engineer evaluates several possible designs and selects the optimum considering certain types of criteria. Therefore the aims of this research project are to classify and summarise typical optimisation applications and their objectives and constraints in aircraft structural design to help engineers identify their optimisation problems, and develop a systematic framework and recommendations for approaches to various problems in this domain to inspire engineers to solve their optimisation problems.

2 LITERATURE REVIEW

2.1 Introduction

Design is "an activity that facilitates the realisation of new products and processes through which technology satisfies the needs and aspirations of the society" (Saxena, 2005). There are many kinds of design, and engineering design is one of them which are applied widely in almost every fields of people's life. Engineering design is an activity that requires specialised integrity and accountability, uses scientific laws and insights, bases on a particular practice and provides the preconditions to achieve the solution (Pahl, 2007).

Engineering design is generally considered and developed in 4 steps, as shown in Figure 2 (Saxena, 2005).

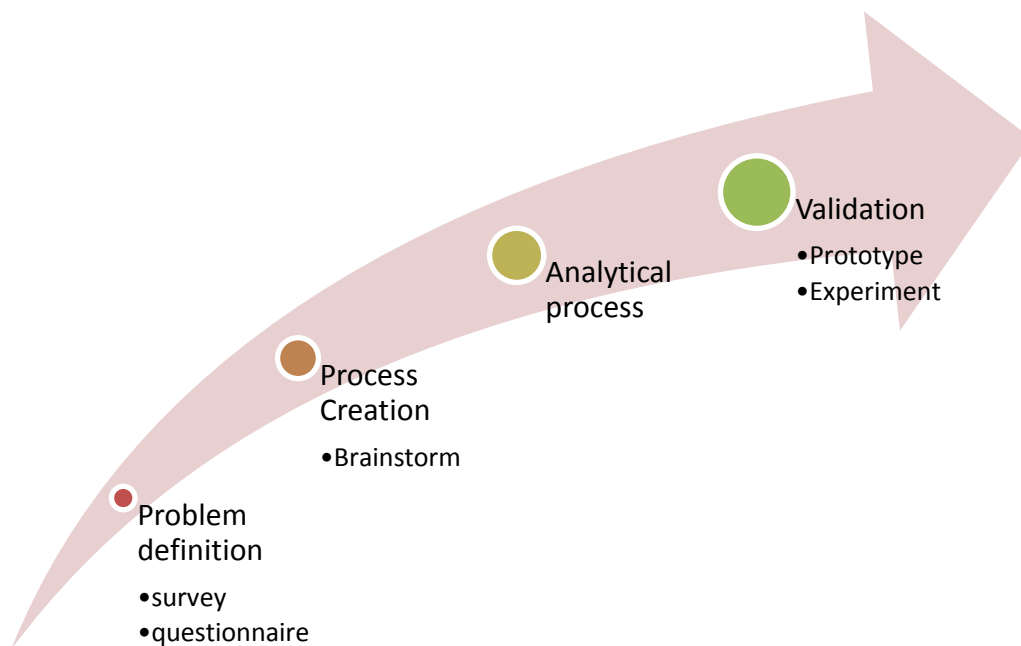


Figure 2 Engineering design steps (Saxena, 2005)

In the problem definition stage, designers need to extract the function requirements of an engineering part from a mass of disordered facts in the original problem. Usually a survey or questionnaire is used to collect data for observation.

Then, various solutions and approaches will be created based on the designer's experience and knowledge. It is very common to adopt brainstorming in groups to achieve this purpose. These solutions will be evaluated and compared so as to find several feasible approaches.

The third phase, analytical process, is to analyse and improve the functional performance such as strength and reliability, cost determination and environmental impact by changing the geometry and/or material. The analytical process is an iterative approach to optimise the functional performance and meet the requirements extracted from the first phase. Numerous results are assessed at the same time or independently and the optimum result complying with most or all requirements can be selected.

Finally, designers need to build and test a prototype, or try experiments to validate if the optimum result satisfies initial function. Modifications are allowed if the prototype or experiment fails to fulfil the requirement. Meanwhile this phase will also connect the design to the manufacturing.

Structural design is a kind of engineering design which takes a significant role throughout the whole development process of an aircraft. It is an iterative process of applying mechanics and previous knowledge to generate a functional, cost-effective, and safe structure.

For the aircraft structures, a number of components should be designed as shown in Figure 3 (Niu, 2006). All structures must be reliable even in the extreme weather and all climates, and must work effectively and efficiently in corrosive environments for 15 to 20 years with maximum maintainability. Meanwhile the weight should be controlled as well as possible to minimise the cost. The design needs to keep pace with the latest materials and processes which may improve the performance or reduce the cost.

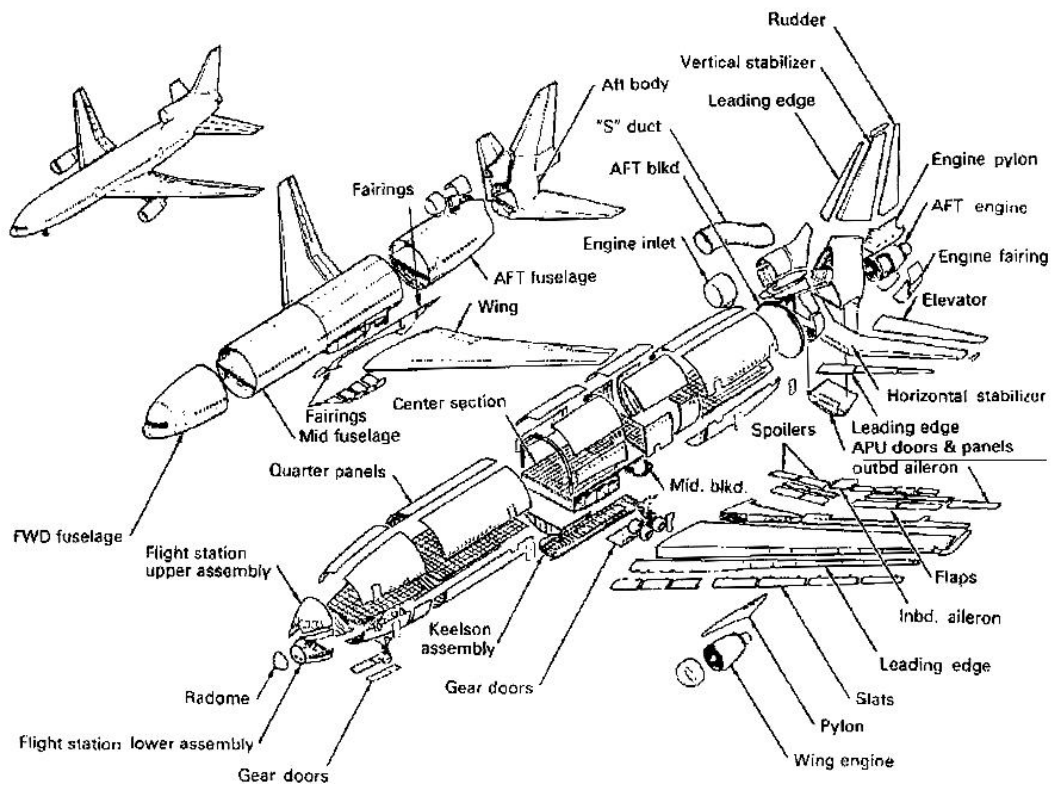


Figure 3 Commercial aircraft structural breakdown (Niu, 2006)

Optimisation is a field of management science also called mathematical programming that aims to discover the feasible optimums that meet the requirements of the objectives (Deb, 2001). The motivation of optimisation is to explore the available limited resource in a manner that maximizes utility, because within a selected concept there may be many possible designs that meet the requirements and constraints. From the structural point of view, to achieve the best mechanical behaviour, say, maximum stress/weight ratio or minimum deflection and meanwhile to respect pre-condition, is the kernel of the procedure (Kirsch, 1993). This process is illustrated in Figure 4.

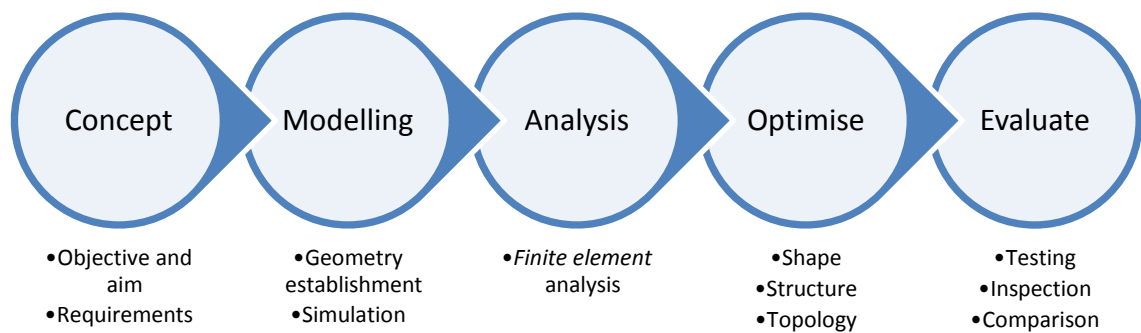


Figure 4 Structural design and optimisation (Kirsch, 1993)

Design optimisation is an iterative process of repeated modelling, analysing and modifying which can improve the design (Roy, 2002). This process will considerably increase the design time and be affected by engineers' ability. So it becomes quiet necessary to develop an optimisation process which can carry out the optimisation automatically using the design tools.

2.2 Modelling of Structures

2.2.1 Computer-aided Design

Computer aided design (CAD) is an activity using computer systems to create, modify, analyse or optimise a design (Narayan 2008). CAD software is used to enhance the efficiency of the designer, raise the quality of design, and to generate the drawings and other documents for manufacturing.

CAD can generate more information apart from geometry; the outcomes of a CAD document also deliver additional product information, including materials, manufacturing methods and tolerances.

2.2.2 CAD Tools Review

2.2.2.1 CATIA

CATIA, developed by the French company Dassault Systemes SA, is a cross-platform commercial 3-D CAD design software. As the core of the product lifecycle management platform introduced by Dassault Systemes, CATIA is one

of the most important tools which is widely used in mechanical equipment & systems design in aerospace and automobile industries.

CATIA has a capacity to expand its function by using VB, C++ and CAA to develop external programme.

2.2.2.2 AUTOCAD

AutoCAD is an interactive graphics system developed by Autodesk for 2D and 3D drawing and design. It can be used to create, browse, manage, print, share and accurately present information of design graphics. AutoCAD supports various APIs, including Auto/Visual LISP, .NET and VB. The object ARX, a C++ class library, is also supported by AutoCAD. The APIs extend AutoCAD functions in certain particular occasions.

AutoCAD can open and edit .DWG and .DXF documents. Although AutoCAD can be used for 3D modelling, it is only well known as a 2D design tool in various industries.

2.3 Finite Element Analysis of Structure

2.3.1 Introduction

Structures are often analysed with finite element analysis methods which have developed for many years to be the fundamental and essential tools. An initially designed structure is analysed based on the loads to derive deflections, stresses and strains. Engineers can amend the geometry to minimise weight or avoid failure. Recently, structural optimisation has been integrated with finite element analysis to optimise the structure in terms of minimum weight considering certain constraints. FEA is proved to be very useful and there are countless cases of substantial weight reduction using these methods.

2.3.2 Linear Static Analysis

Common analysis types in CAE include: dynamic analysis, non-linear analysis, linear static analysis, buckling analysis, thermal analysis, and crash analysis.

In linear static analysis, the FE (Finite Element) solver always follows a straight line from base to the deformed state in equilibrium condition or when the force is static. The complete equation to be solved in a linear static FE solver is

$$\mathbf{F} = \mathbf{K} * \mathbf{u}$$

where \mathbf{F} is the vector of all applied external forces and moments, \mathbf{K} is the stiffness matrix of the model depending on the material and geometric properties, and \mathbf{u} is the nodal displacement vector. In a linear analysis, \mathbf{K} is constant (Kirsch, 2008).

2.3.3 FEA procedure

The procedure to carry out finite element analysis is summarised and illustrated in Figure 5 (Bathe, 2006). Physical problems usually involve real structures or structural components subjected to certain loads. A physical problem needs to be idealised into a mathematical model in order to be solved with Finite Element Analysis. Considering the FEA approach is a numerical procedure, the solution accuracy is of great importance. Hence, one of the most critical factors in FEA is establishing suitable mathematical models. If the degree of accuracy is not satisfying, the numerical analysis has to be re-conducted with better mesh or finer parameters to obtain a more accurate model (Bathe, 2006).

As long as a mathematical model is solved and interpreted, the mathematical model may be refined so as to obtain more accurate details on the response. Additionally, the physical problem could be modified in some cases, which may potentially result in adding extra mathematical models and finite element solutions.

The general procedure of the displacement-based FEM can be summarised as follows (Bathe, 2006):

- a) Idealising the entire structure as an assembly of elements connected at joints;
- b) Identifying the unknown displacements to set up the response of the idealisation;

- c) Formulating and solving the equilibrium equations corresponding to the unknown displacements;
- d) Calculating the internal stress with the given displacements;
- e) Interpreting the displacement and stress calculated in the previous step.

This procedure will be discussed in detail in Section 3.3.2 FEA Technique.

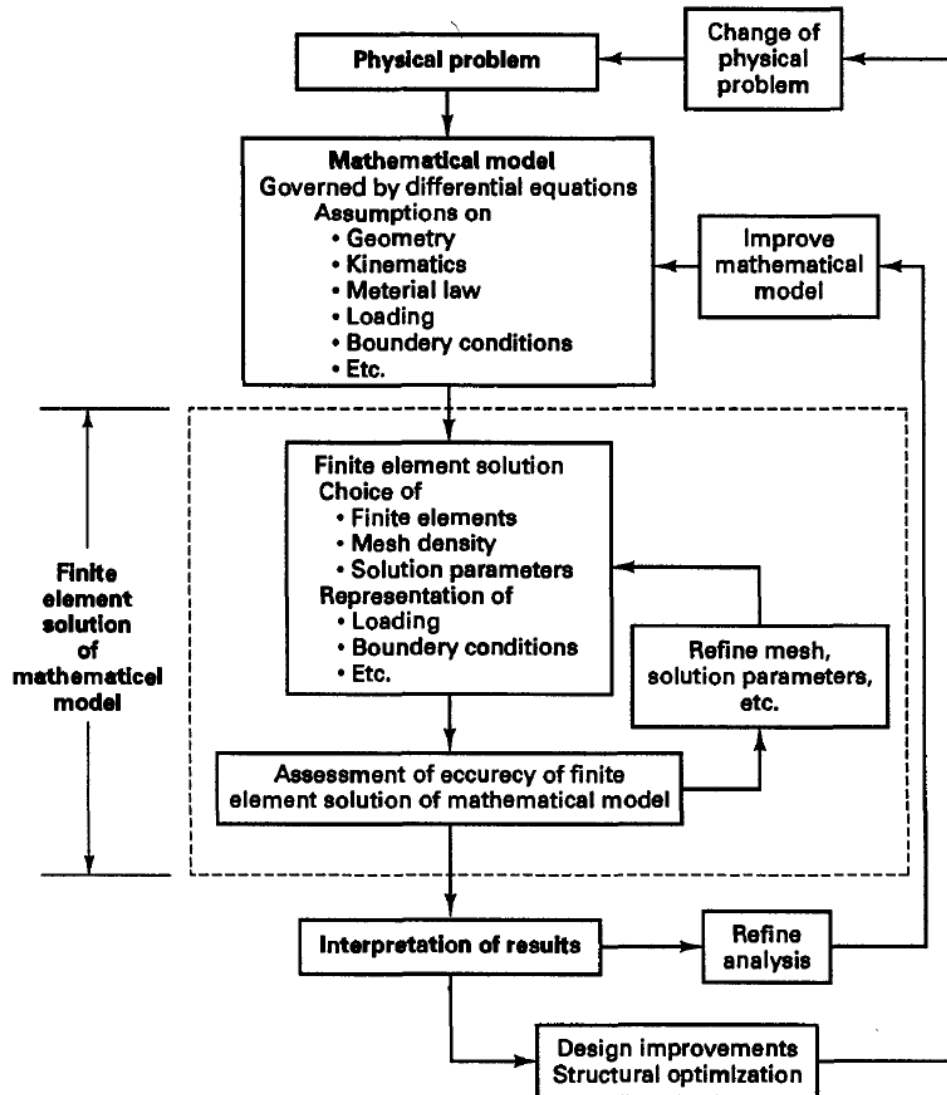


Figure 5 FEA General Procedure (Bathe, 2006)

2.3.4 FEA Tools Review

The FEA software tool is widely used in aircraft industry. It enables users to synthesise and optimise their designs, which is crucial for designers to evaluate the impact of modifications, achieve the improvement of the baseline designs,

and make sure that various kinds of criteria are fulfilled. With particular techniques it is possible to analyse stress performance and optimise discrete variables.

2.3.4.1 Pre-processor

The pre-processor is used in the pre-processing session to create the mesh, the boundary conditions and the properties. Popular pre-processor software includes PATRAN, ANSYS and HYPERMESH.

2.3.4.2 Processor/ Solver

The processor resolves the mesh and produces two types of file. One is a text file containing the outcomes of the run, and the other provides information to the post-processor to illustrate contours of the data generated by the solver. NASTRAN, ABAQUS, ANSYS, LS-DYNA, RADIOSS and OPTISTRUCT are popular processor software.

2.3.4.3 Post-processor

The post-processor is used for plotting the results obtained in exclusion session. HYPERVIEW and PATRAN are usually employed as the post processor in aerospace industry.

2.4 Structural Optimisation

2.4.1 Introduction

Structural optimisation generates a component design which exhibits maximum structural utility subject to a set of functional requirements and constraints on the component's structural behaviour (Chapman, 1994).

There are many types of structural optimisation problems: sizing, shape, topology and topography. Topography is generally regarded to be one advanced form of the shape optimisation. The sizing, shape and topology optimisation problems are very common in the structural design (Lau, 2009). Figure 6 illustrates the differences among shape, topology and sizing optimisation.

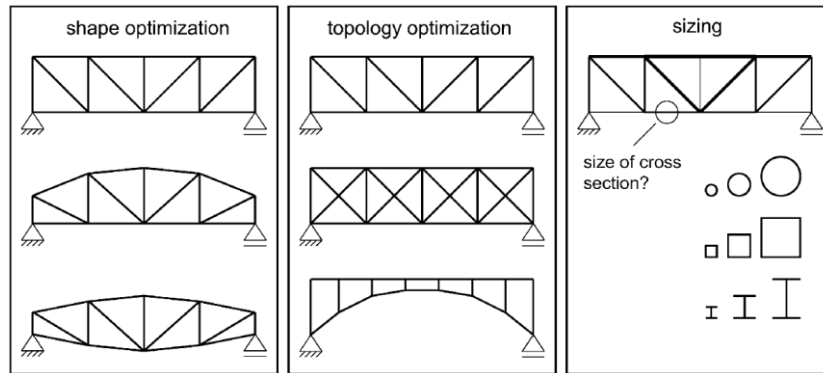


Figure 6 Basic structural optimisation problem types
(Ledermann, 2006)

2.4.2 Sizing optimisation problem

Sizing optimisation performs optimisation by holding a design's shape and topology constant while modifying specific dimensions of the design (Chapman, 1991). Hence, the design variables control particular dimensions of the design, and the values of the design variables define the values of the dimensions. Optimisation therefore occurs through the determination of the design variable values, which correspond to the component configuration.

In sizing optimisation (Figure 6(a)), the optimum combination of various size variables (the length, height, cross-section area etc.) are discovered based on the fixed shape and constant topology distribution. However, it is very important that the material distribution should be optimised before the sizing optimisation, or it will be irrational (Lau, 2009).

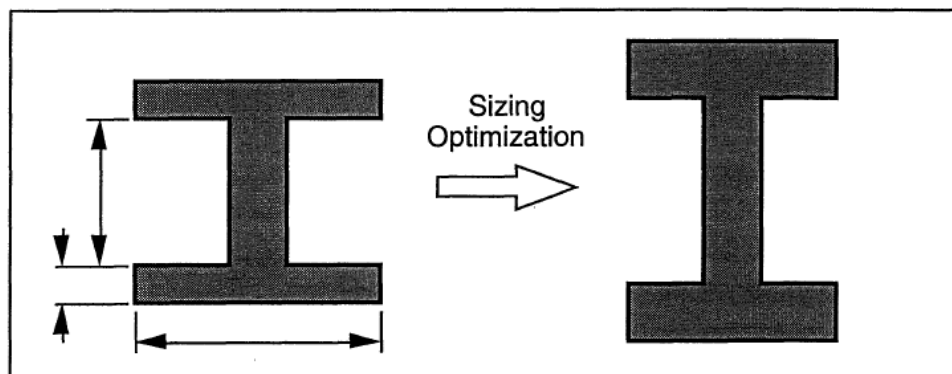


Figure 7 Sizing optimisation (Chapman, 1991)

2.4.3 Shape optimisation problem

Shape optimisation performs optimisation by holding a design's topology constant while modifying the design's shape (Chapman, 1991). Hence, the design variable controls the design's shape, and defines the particular geometry of the design. Optimisation therefore occurs through the determination of the design variable values which correspond to the component shape providing optimal structural behaviour.

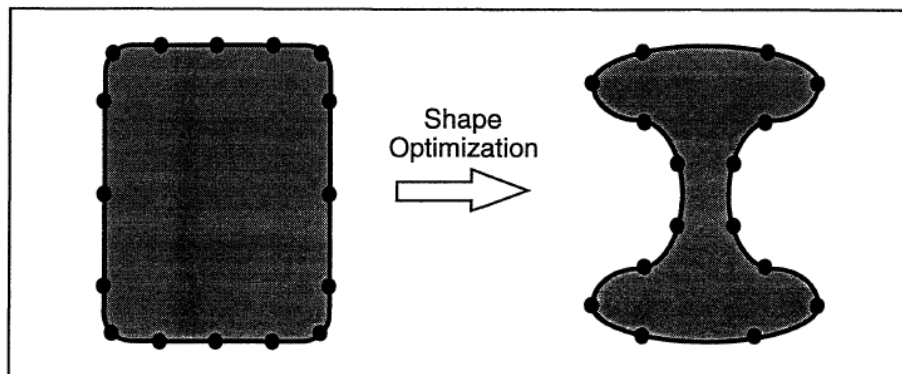


Figure 8 Shape optimisation (Chapman, 1991)

Shapes need to be defined first, including Mesh morphing and perturbations, mesh topology must be maintained and shapes are then assigned to design variables. Perturbations are exported with the solver input deck. Then carry out the morphing with Domain and Handle.

Topography optimisation is considered to be a special type of shape optimisation applied on 2D to determine the optimum topography of a component. In the topography optimisation, the design space is pre-defined and a pattern of parameterised stiffeners in the design space is created.

2.4.4 Topology optimisation problem

Topology optimisation performs optimisation by modifying the topology of a design (Chapman, 1991). Hence, the design variables control the design's topology, and the values of the design variables define the particular topology of the design.

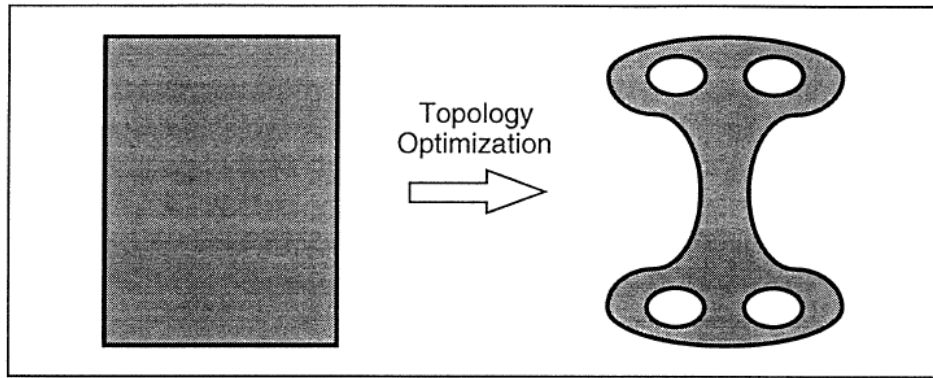


Figure 9 Topology optimisation (Chapman, 1991)

Topology optimisation is more complicated because of it involves the optimisation of both the external boundary and distribution of the internal material within a structure.

The design space is selected parts which are designable during optimisation process. For example, material in the design space of a topology optimisation. The design space should be defined to start the topology optimisation.

The sizing optimisation is supposed to be the least-complex of the three structural optimisation categories. Note that sizing optimisation typically occurs as an incidental by product of the shape optimisation process. Topology optimisation therefore occurs through the determination of the design variable values which correspond to the component topology providing optimal structural behaviour. Note that sizing and shape optimisation typically occur as incidental by products of the topology optimisation process (Chapman, 1991).

In practice, there are typically three phases in the design process. The first one is the concept design phase, in which the baseline design is generated according to the design requirements and specifications. Then topology optimisation is applied in the second stage: the concept design phase. This will remove most excess material and produce a general configuration, which will be interpreted to a CAD model. Finally the sizing and shape optimisation is applied to achieve a better performance (Krog, 2002). The optimum structure generated from the sizing and shape optimisation is based on the initial topology design. Hence, without an optimum structure obtained in topology

optimisation, it will be not possible to find the final optimised structure by sizing and shape optimisation (Lau, 2009)

2.4.5 Material selection in structural optimisation

In aircraft design, the material selection is of great importance. There are mainly 4 types of material which are widely used in aerospace industry: steel, aluminium alloys, titanium alloys, and fibre reinforced composites. During the selection of material, the performance of tension, compression, bending and torsion should be considered (Lopes, 2008).

The work conditions (such as temperatures, compressibility effects, moisture and fluid exposures, radiation, and lightning-strike) are critical in the material selection (Huda, 2012).

In literature, although there are a large number of publications on material selection, not many can be found regarding the material selection in aircraft structural optimisation. The material selection in structural optimisation can be roughly divided into three types: composite material structure optimisation (out of scope of this thesis), eco-friendly structure optimisation and structural-acoustics optimisation.

Nowadays, the material selection in most of the structural optimisation is carried out with consideration of the mechanical behaviour only. With the increasing awareness of environment problems, the environmental impact will gradually be taken into account in material selection of structural optimisation. An eco-indicator is often adopted to measure the environmental impacts, and convert them into a single value for materials (Zander, 2012). Ermolaeva et al. demonstrated how to employ the eco-indicator as an objective to select the material in the structural optimisation for sandwich panels (Ermolaeva, 2004). It is found that the all-Al-alloy and Al-foam sandwich structures perform well in terms of recyclability. However, they keep higher eco-indicator value over the life cycle concerning the environmental impacts. The low-density phenolic foam is selected in this structural optimisation. Qiu et al. developed an approach combining the structural design and material selection to improve environmental

performance of structures (Qiu, 2013). An optimisation model was developed with the discrete variable of material to minimise the environmental impact. A candidate material combination was generated by integrating approaches of qualitative and quantitative screening, as demonstrated in Figure 10. The overall environmental impact of the materials was measured with the Eco-indicator. Two sets of structural optimum designs were evaluated with ideal and negative-ideal materials selected respectively. With the comparison of the environmental impact index for each candidate material combination, the optimum can be found and the structural optimisation finished.

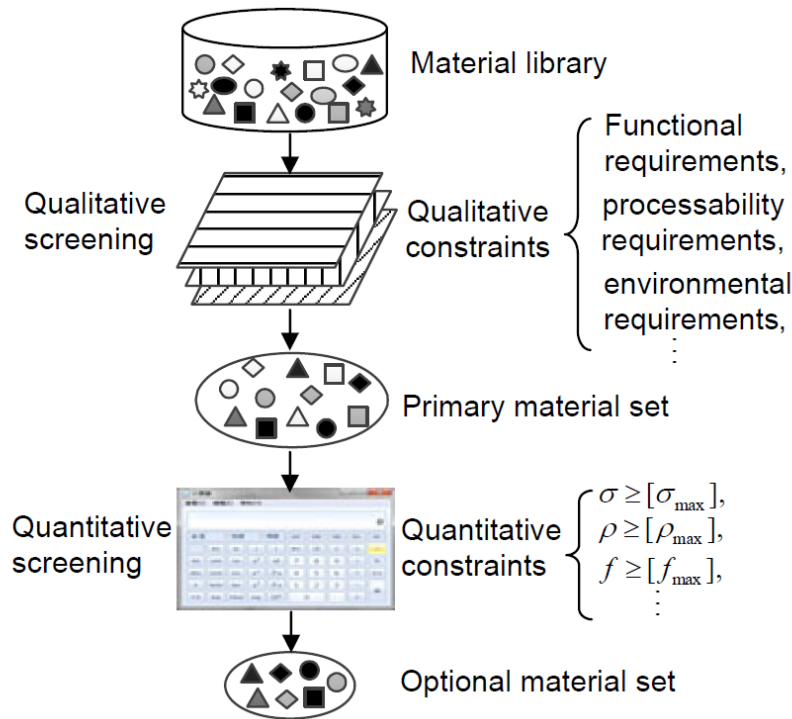


Figure 10 Development of the candidate material combination (Qiu, 2013)

The selection of materials is also conducted in structural-acoustics optimisation, such as aircraft fuselage optimisation which involves acoustics discipline. Chen et al. introduced the “stacking sequence hypothesis” of metal material to conduct the material selection optimisation (Chen, 2013). The acoustic radiation power is defined as the objective, while the material properties and plies number of hybrid structure are defined as variables. Genetic algorithm (GA) is

deployed to discover the connection between acoustic radiation and the material properties.

As can be found in literature, the composite material selection is frequently conducted in the composite structural optimisation. This will be studied further in the future research.

2.4.6 Manufacturing constraints

Topology optimisation should consider manufacturing constraints, or the result could be infeasible. There are mainly kinds of manufacturing constraints (Zhou, 2002):

- a) Minimum member size control: specifies the smallest dimension to be retained in topology design. Controls check board effect and discreteness.
- b) Maximum member size control: specifies the largest dimension allowed in the topology design. It prevents large formation of large members and large material concentrations are forced to more discrete forms.
- c) Pattern grouping / repetition: can be applied to enforce a repeating pattern or symmetrical design even if the loads applied on the structure are unsymmetrical or non-repeating.
- d) Draw direction / extrusion constraints: can be applied to obtain design suitable for casting or machining operations by preventing undercut or die-lock cavities.
- e) Extrusion constraints in topology optimisation, constant cross-section designs can be obtained for solid models – regardless of the initial mesh, boundary conditions, or loads.

Figure 11~Figure 15 compare the absence and present of different manufacturing constraints .

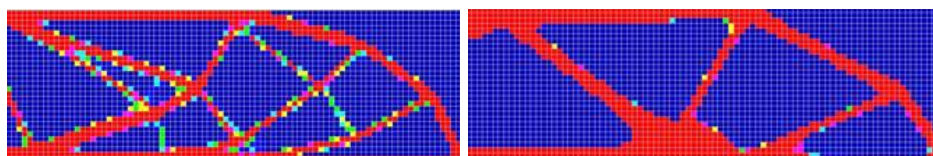


Figure 11 Comparison of Minimum member size constraint(ALTAIR, 2009)

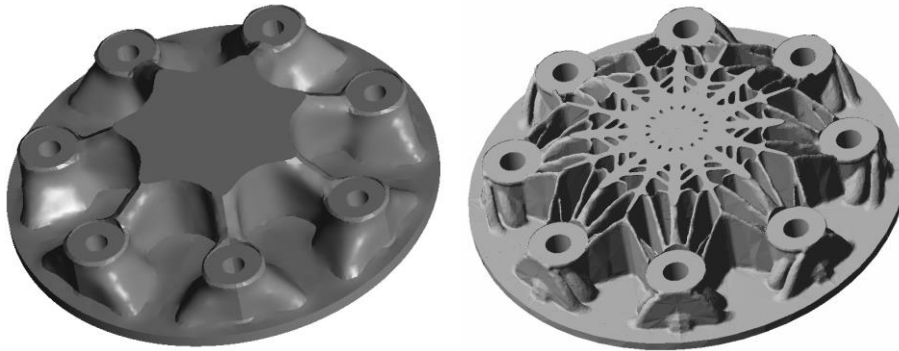


Figure 12 Comparison of Maximum member size control constraint(ALTAIR, 2009)

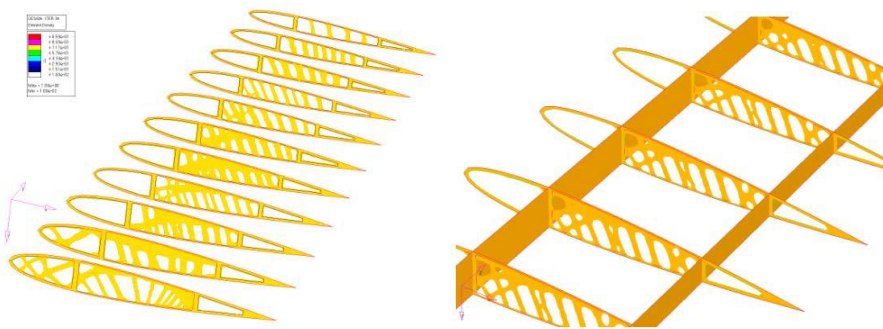


Figure 13 Comparison of pattern repetition constraint(ALTAIR, 2009)

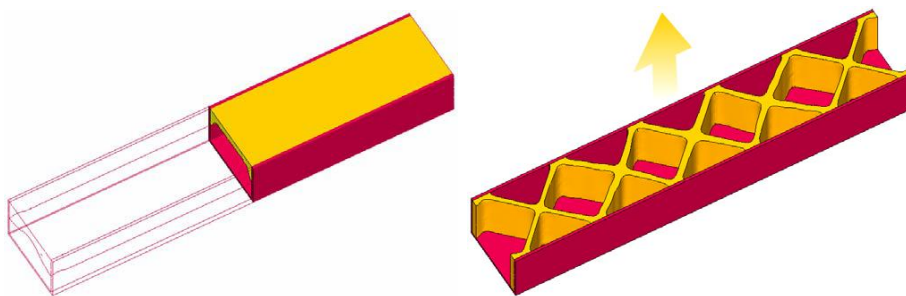


Figure 14 Comparison of draw direction constraint(ALTAIR, 2009)

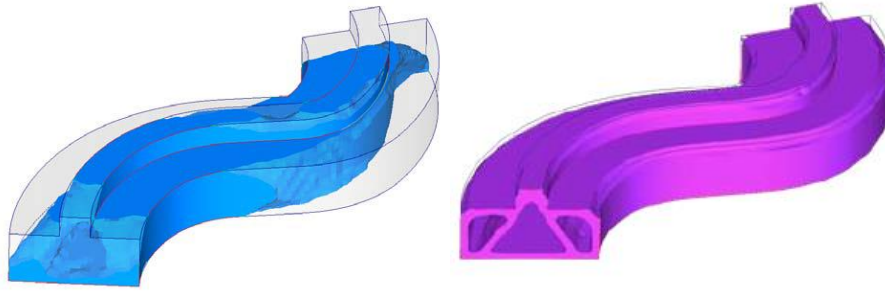


Figure 15 Comparison of extrusion constraint (ALTAIR, 2009)

2.5 Mathematical Optimisation Theory

2.5.1 Introduction

The mathematical definition of an optimisation problem can be given as a process to:

$$(\text{SO}) \left\{ \begin{array}{l} \text{minimise } f(x, y) \text{ with respect to } x \text{ and } y \\ \text{subject to } \left\{ \begin{array}{l} \text{constraints on } y \\ \text{constraints on } x \\ \text{equilibrium constraint} \end{array} \right. \end{array} \right. \quad (\text{Christensen, 2008})$$

Design variables are system parameters that are varied to optimise system performance. The objective function returns the response or result of the design variables. The constraint functions are bounds on response functions of the system that need to be satisfied for the design to be acceptable. A design is feasible if it satisfies all the constraints, otherwise it is infeasible.

2.5.2 Optimisation problem types

2.5.2.1 Single objective design optimisation

The single objective optimisation is the basic technique in aircraft structural design. Only one objective is set to be minimum or maximum, with one or more constraints that the optimisation should meet at the same time.

2.5.2.2 Multi-objective design optimisation

The Multi-objective design optimisation (MOO), also known as multi-criteria optimisation, is defined as an approach to discover solutions which deliver the optimum of more than one objective (Rangaiah 2009). There could be numerous optimums for a multi-objective optimisation. MOO involves special approaches or allowing for more than one objective and evaluating the results to be achieved.

The multi-objective optimisation turns out to be more challenging with more objectives and existing multi-objective optimisation algorithms are not able to achieve a satisfying result with more than five objectives (Corne 2007).

The objective for a complicated multi-objective optimisation problem is to discover various solutions spotted on the Pareto front (Oduguwa, 2007).

2.5.2.3 Multi-disciplinary design optimisation

The Multidisciplinary Design Optimisation (MDO) is a series of engineering systems design approaches which processes a number of disciplines (Balesdent 2012). The MDO methods aim to find the global optimum solution from the couplings and synergisms of several different disciplines (Sobieski 1993). The key factors of the MDO problem are the accuracy of the result, the time of the calculation and the robustness of the optimisation process (Balesdent 2012).

MDO can be summarised as the development of strategies that from current analysis tools (FEA) and optimisation techniques help the engineers to take the best decision during the design process in order to obtain an optimised complex products or systems (Depince 2007).

2.5.3 Evolutionary computing and genetic algorithms

The evolutionary algorithm (EA) can be defined as a set of random optimisation techniques that simulate the process of natural evolution (Zitzler 2004). The EAs appeared as early as the late 1950s, and later some evolutionary methodologies, mainly genetic algorithms, evolutionary programming and evolution strategies have been adopted (Bäck 1997).

The genetic algorithms adopt an evolutionary, "survival-of-the-fittest" optimisation mechanism. A set of chromosomes is designed to evolve, with the next generations of new chromosomes to develop from, and replace the older generations. Highly quality chromosomes survive to develop the subsequent generation. After several generations of evolution, the general quality of chromosomes will rise due to characteristics of better chromosomes. The flowchart of the genetic algorithm flowchart is illustrated in Figure 16 (Chapman, 1991).

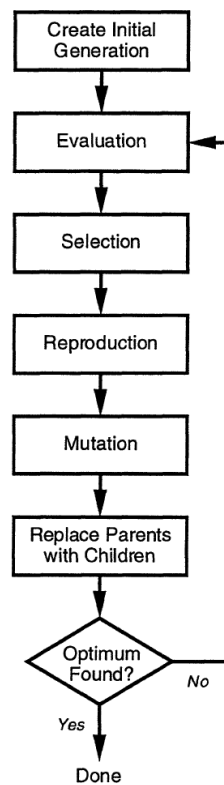


Figure 16 Genetic algorithm flowchart (Chapman, 1991)

2.5.4 Optimisation tools review

The optimisation tools can be divided into free open source software and commercial software. At present there are many tools available to solve the optimisation problem. Table 1 shows the comparison of popular optimisation tools and illustrates a general background of the optimisation in practice. This is essential to identify which software will be focused on in the questionnaire and interview in the next stage.

Table 1 The comparison of popular optimisation tools

software	company / author	country	Features	Applied in
PPL	Bugseng	Italy	MILPs, simplex algorithm,	Information Industry,Biochemical Industry
JOPTIMIZER	Apache Maven	Unknown	Newton unconstrained, barrier interior point method, primal dual interior point method	Automobile Industry
COIN-OR SYMPHONY	COIN-OR	US	MILPs, simplex algorithm,	Information Industry
IOSO	Sigma Technology	Russia	No Info	Aerospace,Automotive,Metallurgy,Construction,Oil & Gas,Marine,Electronics cooling ,Technological and business processes ,Optical systems ,Bridge design ,Biotechnology
HEEDS MDO	Red Cedar Technology	US	Genetic algorithm, SHERPA algorithm, Multi-objective SHERPA, Sequential quadratic programming	Academic,Aerospace,Automotive,Biomedical,Defense,Manufacturing and Processing,Materials,Motorsports
Inverse	loptlib	Slovenia	simplex algorithm,	No info
Isight	SIMULIA	US	NLPQL, MMFD, NSGA II, NCGA	Aerospace industry, Energy industry, Marine industry
HyperStudy	Altair	US	MOGA, GMMO	Aerospace industry, Automotive,Biomedical , Electronics, Energy, Marine
modeFRONTIER	Esteco	Italy	NSGA-II, MOSA, MOGT, MOPSO, FAST, SAnGeA, Evolution Strategy	Aerospace industry, Appliances,Automotive,Biomedical , Food, Turbomachinery, Electronics, Energy, Marine

2.6 State of Art

Traditionally, there are two approaches to integrate CAD system and other applications, namely 'archive file' approach and 'neutral file' approach (Roy 2002). Roy et al. adopted an approach to integrate the optimisation algorithm straight to the CATIA through its API. The API interface used by Roy et al. had a capacity to implement the graphics interactive interface (GII) which can re-define the communication between different systems.

Multi-objective evolutionary algorithms (MOEAs) become very popular due to their outstanding accessibility and flexibility. The major disadvantage is the high computational cost (Arias-Montano, 2012).

Engineering design is still optimised mainly by comparing several candidate designs to decide manually which one is the best solution, considering about one discipline or objective such as the weight or stress. This manual method is frequently restricted to choosing recognised designs, which may result in the failure of identifying any unfamiliar global optimum (Roy, 2008).

A survey of multi-objective optimisation methods for engineering was carried out by Marler et al in 2004. It is found that, to different extents, genetic multi-objective algorithms can be effective in finding the Pareto front. If there are numerous objective functions, it will cost a lot to decide the optimum solution, even for an estimated result (Marler, 2004).

There are quite a few optimisation approaches in design optimisation: human knowledge-based engineering to intelligent (adaptive) algorithms (Roy, 2008). A study conducted by R. Roy et al. shows the popularity of different design optimisation approaches in literature as illustrated in Figure 17 (Roy, 2008). It can be found that multidisciplinary optimisation has become a spotlight in recent researches on optimisation.

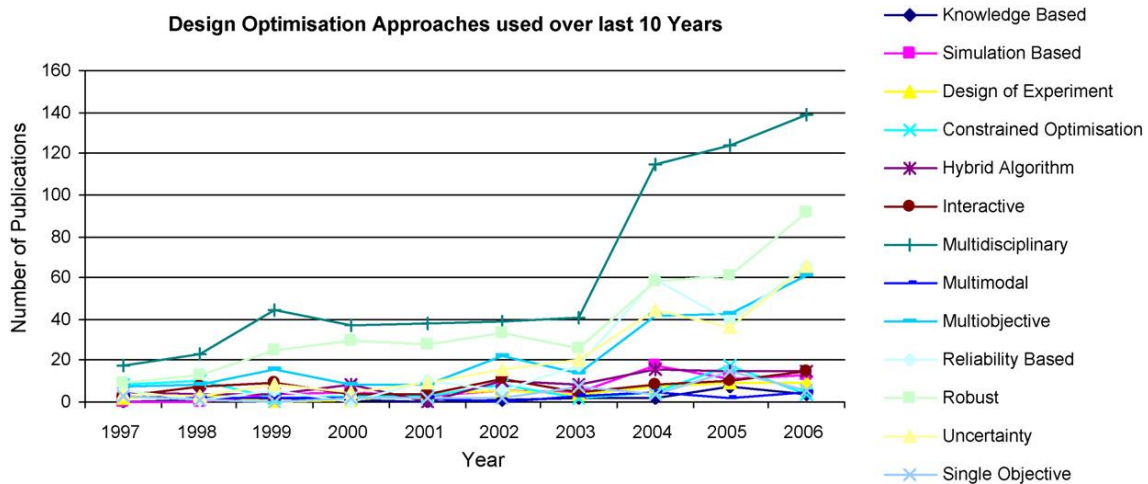


Figure 17 Design Optimisation Approaches in literature (Roy, 2008)

Numerous studies on structural optimisation of the overall aircraft and each component have been conducted in recent years.

Regarding the overall structural layout optimisation, an approach was generated by Allen et al. to optimise structures of different types subject to certain load conditions (Allen, 2012). Allen et al. investigated the drawbacks of conventional techniques and proposed the Hyper-heuristic approach, including perturbation analysis, parameter control, heuristic selection and population distribution. Olympio et al. employed a hybrid MOEA to create a constrained topological method to morph the aircraft structure (Olympio, 2008). The local strain was adopted to define the constraint so as to prevent the deformation or failures. The FEA was conducted to assess the objective functions. The topologies are found using a multi-objective genetic algorithm coupled with a local search optimiser. The 1D morphing and shear compression morphing are introduced and deployed to define the structure configurations.

For generic parts such as beams and panels, an integrated technique for shape parameterisation (CAD) and process parallelisation has been introduced (Langer, 2002). The MOEA developed by Langer et al. deploys a combination of real and integer representation for continuous/discrete variables with different operators. The process parallelisation adopted in this approach considerably decreases computing time. Nikbay et al. employed a mix of approaches for multi-disciplinary analysis and optimisation, especially focusing on the aero-elastic

optimisation problems involving aerodynamic and structural discipline (Nikbay, 2008). The technique Nikbay et al. employed in the MDO analysis was based on NSGA-II.

For the wing component, Locatelli et al. conducted the weight optimisation of a supersonic wing box in 2010. Their work presents how to conduct mixed topology and sizing optimisation using curvilinear spars and ribs (Locatelli, 2010). The wing box is also optimised in Schuhmacher's study. He adopted MDO methods to optimise the wing boxes of a new regional jet (Schuhmacher, 2002). The MDO methods are also widely employed to define the wing structures configuration, particularly in the preliminary design phase. Rajagopal et al. adopted the MDO method to optimise the wing of an unmanned aerial vehicle. The endurance and weight performance were maximised with NSGA-II technique (Rajagopal, 2009).

For the fuselage component, Tooren et al. developed a technique called Design and Engineering Engine (DEE) to solve optimisation problems involving structural, acoustical and thermal disciplines for the fuselage (Tooren, 2007). Additionally, Hansen et al. deployed the evolution strategy to optimise the fuselage component of a blended Wing-Body aircraft (Hansen, 2008). Three types of fuselage were analysed: single, double and sandwich. The optimisation was carried out with deterministic, gradient-based techniques of NASTRAN SOL200.

For other components, the number of publications is relatively small. Saleem et al. performed non-parametric topology optimisation on a vertical stabiliser component using conventional FEA approach (Saleem, 2008). A new algorithm called Interactive Multi-Objective Particle Swarm Optimization (IMOPSO) was successfully developed by Weigang et al. to carry out the pylon component optimisation (Weigang, 2007).

As the classification of popular optimisation applications in airframe design is one of the major objectives of this study, detailed analysis will be presented in Section 5.2 "Airframe Optimisation Classification".

2.7 Summary

The definition and process chart of engineering design are introduced in this chapter. Particularly, the aircraft airframe structures are briefly presented, which will be useful in the optimisation classification in the chapter 5.

Since the modelling is the basis of structural design and optimisation, the CAD techniques and tools are introduced and analysed in this review. Then the FEA fundamental knowledge is acquired, such as the procedure and tools of FEA.

Subsequently, the structural optimisation problems are classified as sizing, shape and topology optimisation. Those three types of optimisation are introduced and compared. Material selection and manufacturing constraints are also reviewed.

Through the literature review, general knowledge has been obtained and basic skills have been learnt. Moreover, it provides necessary information to identify the research methodology in the next stage.

3 RESEARCH STRATEGY AND METHODOLOGY

3.1 Introduction

The research strategy is the procedure to find a proper method to carry out a piece of research. The research methodology is in general an instruction system designed to solve problems, with explicit methods (Creswell, J. 1998). Different research strategy is adopted considering different research aims and objectives. Therefore it is essential to define and adopt an appropriate research strategy for a specific project in order to find the methodology to solve problems.

3.2 Research Strategy

Figure 18 shows the workflow of research strategy of this study, including four major phases, namely Research Definition, Information Collection & Analysis, Framework Development, and Case study & Validation.

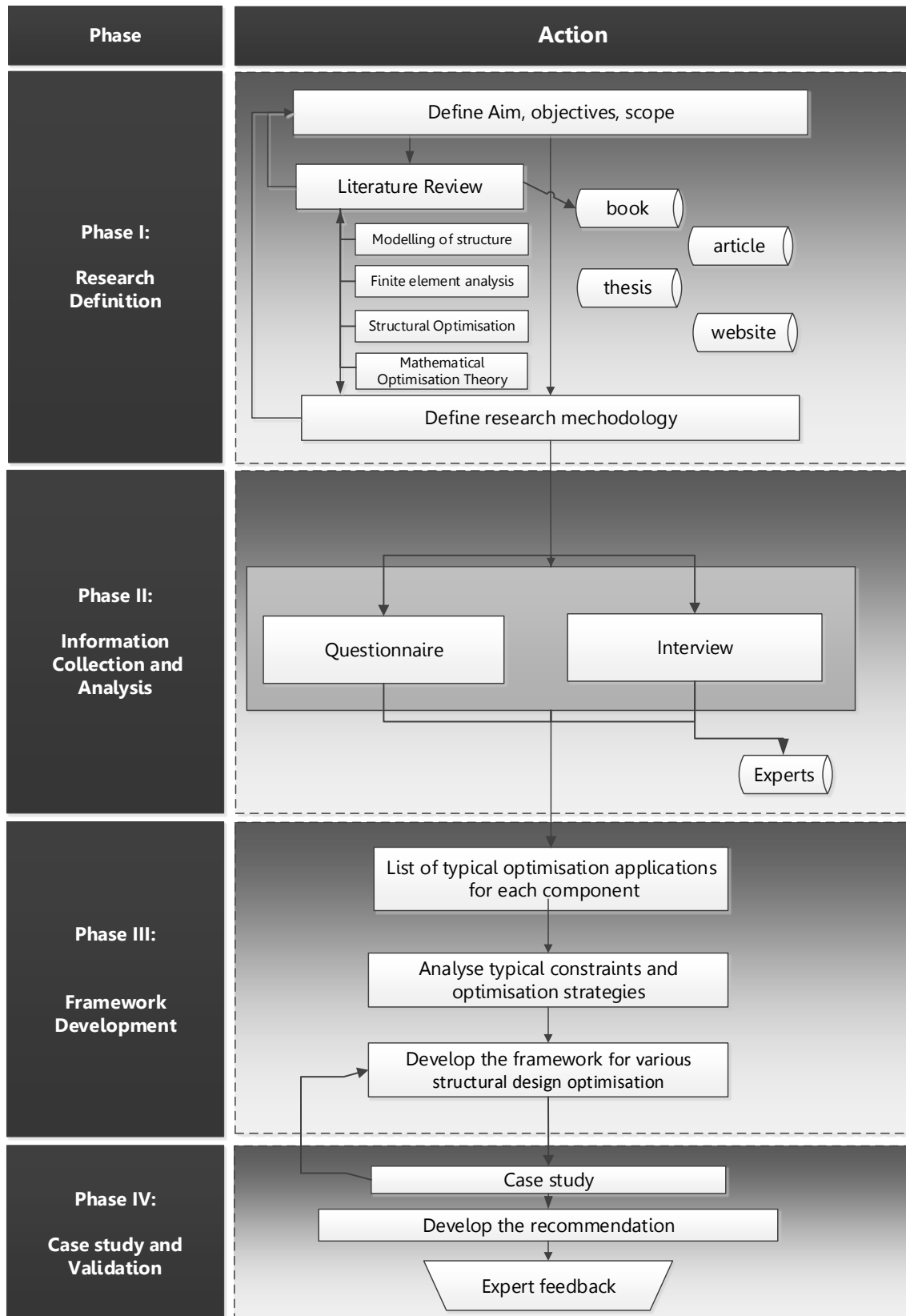


Figure 18: Research Strategy Chart

3.2.1 Phase I: Research Definition

The major purpose of this phase is to develop a clear understanding of this research, including the aim, objectives, scope, deliverables and research strategy.

A wide range literature review is conducted to acquire background knowledge, focusing on structure modelling, finite element analysis, structural Optimisation, and mathematical optimisation theory. Relevant Information and knowledge can be obtained by reviewing papers mainly from the online database of SCIENTEDIRECT, AIAA, Springer and Wiley.

3.2.2 Phase II: Information Collection and Analysis

In order to collect relevant structural optimisation applications and information from various industrial, surveys are carried out with experienced experts. Mainly two methods, namely questionnaire and semi-structured interview, are undertaken in this study so as to obtain sufficient information. Some of this information can be found in project documents or reports within the industry, whilst most could only be required from engineers or experts in practice.

During this period, specific and detailed questions were posed to the experts or designers in order to capture their experience. A questionnaire was sent to representatives from a wide range of industries, including the aerospace industry, automobile industry, relevant universities, and software developing companies. The questionnaire focuses on optimisation problems and strategies, such as typical objectives, input/output parameters, noise, constraints, fitness characters and workflow.

Interviews with experts and academic researchers are also a quality approach to collect useful data. In this study, interviewees are from COMAC and ALTAIR UK Company.

This section also presents the analysis of the data collected from the questionnaire and interview.

The questionnaire form can be found in the Appendix A, and the interview form is in Appendix B. Additionally, the responses of the questionnaire are presented in Appendix C.

3.2.3 Phase III: Framework development

In this phase, typical objectives, constraints and workflow are abstracted mainly from the literature review. Additionally, a framework for various structural optimisations is developed and introduced, which aims to systematically guide users to find a proper approach to conduct optimisation step by step.

The framework shall be applicable for most aircraft structural optimisation, including different types of problem in different design phases. The strategy and procedure to develop the framework are:

- a) Initialisation of the problem. This step is to identify input, create the baseline and define the optimisation problem. In order to find proper approach for different problems, it is essential to classify them into single objective, multi-objective and multi-disciplinary problems.
- b) Selection of the approach. In this study, different approaches are into two types (General approach, and DOE & Algorithmic approach) based on literature review, questionnaire and interview.
- c) Conducting optimisation. The preliminary design phase and the detail design phase are employed in the general approach. The topology optimisation is adopted in the preliminary design phase, while the shape & sizing optimisation is deployed in the detail design phase. For the DOE and algorithmic approach, FEA modules involving mechanical, thermal, acoustic, or/and CFD disciplinary are introduced.

With the help of this framework, even engineers without optimisation experience could decide which approach to adopt and how to carry out the optimisation. The framework is the core of this study, and will be discussed in detail in Chapter 5.

3.2.4 Phase IV: Case Study and Validation

This phase aims to validate the recommended framework, including case study, questionnaire and experts' comments.

Three case studies in engineering practice are carried out, in which CATIA and HYPERWORKS are combined and integrated to conduct the structural optimisation. The proposed approach in the framework is applied to specific cases, and the result is assessed by industrial experts through questionnaire or interview. Experts' feedbacks are gathered and applied to the framework development in this stage. With the results of case study and experts' feedbacks, the accuracy of the recommended approach is validated.

3.3 Research Methodology Introduction

In aerospace engineering practice, there are typically 3 stages to carry out an optimisation: Baseline design, FEA analysis and optimisation. This section introduces the key technique details in each stage. Additionally, the systematic optimisation method and procedure are developed as a framework in Chapter 5, and this research methodology is applied in detail in Chapter 6.

3.3.1 Improved Baseline Design

A baseline design is essential to start an optimisation. For the topology optimisation, the baseline provides the envelop information, such as the geometry boundary and maximum material distribution. For the shape and sizing optimisation, the initial design demonstrates the geometry elements which can be used for the definition of design variables. The draft of a part is usually designed with the intention to fulfil specific functions, while the conflict with other structures is avoided. However, the optimised solution always turns out to be conflicting with certain systems, or incompliant with airworthiness specification. This is especially common in the Chinese aerospace industry at present. Hence, to avoid unnecessary iterations, the framework and recommendations in this study take account of the following aspects in baseline design:

- a) Overall Configuration Arrangement (Aircraft Outline Surfaces);
- b) Neighbouring System (such as Pipeline, Wiring) ;
- c) Surrounding components structure (such as the interior structures);
- d) Airworthiness specifications and regulations.

3.3.2 FEA Technique

FEA technique is adopted in this study to calculate the strength and stress performance, and simulate the thermal and acoustic behaviour. The general procedure of FEA is introduced in Section 2.3.3. In this study, this general procedure can be interpreted and implemented in the following 5 steps.

3.3.2.1 Step 1: Idealisation

FEA problems are usually simplified to shorten the computing time. The idealisation of the physical problem to a mathematical model needs several assumptions (Bathe, 2006). For instance, some 3D problems can be idealised to be 1D or 2D models, as illustrated in Figure 19. In addition, small holes and fillets are often deleted, provided that they are unimportant in FEA process (Boeraeve, 2010).

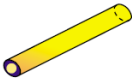

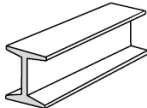

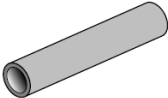





Physical Structural Component	Mathematical Model Name	Finite Element Idealization
	bar	
	beam	
	tube, pipe	
	spar (web)	
	shear panel (2D version of above)	

Figure 19 Examples of Idealisation (Felippa, 2004)

3.3.2.2 Step 2: Discretisation and Assembly

In this step, the discretisation transfers the continuous model into discrete counterparts. The structure model is discretised into a group of elements.

The element attributes are defined in this step. Every element consists of a group of individual nodes. The element geometry is defined by the placement of the Geometric Nodes, while the Connection Nodes are used for defining the degrees of freedom (Felippa, 2004). Some of those nodes are assigned with given displacements, while others are pre-scribed with loads (Roylance, 2001).

A 1-D element is generally a straight line or curved segment. And for 2-D elements they are of triangular or quadrilateral shape. Moreover, typical shapes of 3-D elements are tetrahedral, pentahedral and hexahedral (Felippa, 2004). The element equations are assembled into a collection of global equations that define the properties of the whole model (Boeraeve, 2010). Material and other properties information are assigned in this step.

This process is usually carried out as an initial step toward making them suitable for numerical evaluation and implementation (Boeraeve, 2010).

Mesh quality has a large influence on the accuracy of the FEA results. The element size and density are important factors for meshing. Lower density of the mesh will result in poorer quality of the result, or even cause convergence failure. However, overmuch meshing density will unnecessarily consume extra time. In principle, critical areas where high stress will occur need to be meshed with smaller size elements. Critical areas can be identified with former analysis of a similar part. For a brand new design, roughly estimated critical locations are defined with experts' experience, and be corrected and re-meshed in the following iterations. The most likely areas to find low quality meshing are close to boundary intersections, particularly near the arcs.

Different rules apply in meshing holes and fillets as illustrated in Figure 20 (ALTAIR, 2009).

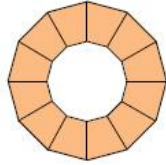
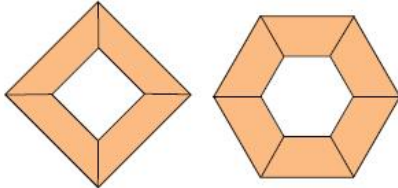
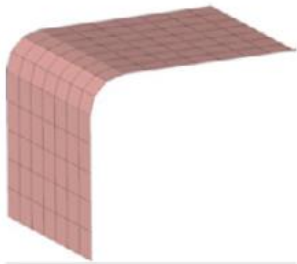
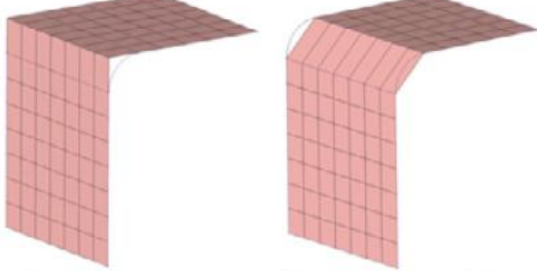
Critical area	General area
 <p>Minimum 12 elements around the hole</p>	 <p>4 to 6 elements</p>
 <p>Minimum 3 elements on fillet.</p>	 <p>Suppress small fillets, 1 element for large fillets.</p>

Figure 20 Meshing rules for holes and fillets (ALTAIR, 2009)

There are many element quality parameters for meshing check, such as skewness, aspect ratio, Jacobian and so on. Those parameters indicate the differences between a selected element and the ideal shape. Ideally the shape for quad elements should be Square, while the shape for triangular elements should be Equilateral triangle. Usually, in aerospace industry, the mesh quality is checked by reviewing faulty elements with at least one of the following properties:

- Ratio of maximum side length to minimum side length is larger than 10;
- Minimum interior angle is smaller than 20 degrees;
- Maximum interior angle is larger than 120 degrees.

Many commercial FEA products provide mesh quality checking tools or functions. In this research, the case studies employ Quality Index module in HYPERWORKS to check the mesh quality.

3.3.2.3 Step3: Application of Boundary Conditions and Load Cases

The element DOF (Degrees Of Freedom) is the number of independent parameters which identifies the state of the element (Felippa, 2004). A rigid can

be defined with six degrees of freedom: three components of translation and three components of rotation, as demonstrated in Figure 21. Additionally, there is often a series of nodal forces corresponding to DOFs.

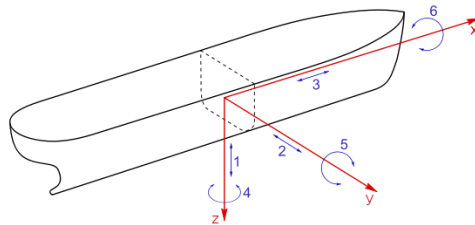


Figure 21 The six degrees of freedom of movement of a ship, from http://en.wikipedia.org/wiki/File:Broesen_shipsmovemensonthewave.svg

There are two types of boundary conditions: Essential boundary conditions and Natural boundary conditions. A prescribed node displacement is a typical essential boundary condition, while the boundary condition involving load or force is classified as natural boundary condition. Performing the essential boundary condition-based FEM technique, the natural boundary conditions are also considered by evaluating the externally applied nodal point force vector (Bathe, 2006). In aircraft structural design, the following boundary conditions are very common (Felippa, 2004):

- a) Ground or support constraints
- b) Symmetry or anti-symmetry conditions
- c) Ignorable freedoms
- d) Connection constraints

The boundary and load information can be obtained from previous experiments or simulations. This is extremely applicable for AIRBUS or BOEING since they have a range of aircraft models. However, when it comes to a brand new design, the initial boundary conditions and load cases may be estimated by performing the similarity analysis. In some cases, several requirements from the airworthiness regulations have defined the maximum or minimum performance data of the structure, which can be used directly. For instance, according to Federal Aviation Regulations (FAR) Part 25, the maximum force on the

emergency slide handle shall be less than 300lb (FAA, 2010), which can be defined as the load input in FEA setup.

3.3.2.4 Step 4: Processing and calculation

The data defined in the previous steps is delivered to the processor or solver, which calculates and processes a set of linear or non-linear mathematical equations.

The matrix method is essential for simplification of the formulation of the stiffness equation, which boots the computing efficiency of the processor. As a fundamental equation in the stiffness or displacement method of FEA, the global stiffness equation can be interpreted in the following matrix form (Langer, 2002):

$$\begin{bmatrix} K_{11} & K_{12} & \dots & K_{1n} \\ K_{21} & K_{22} & \dots & K_{2n} \\ \dots & \dots & \dots & \dots \\ K_{n1} & K_{n2} & \dots & K_{nn} \end{bmatrix} \begin{Bmatrix} d_{1x} \\ d_{1y} \\ \dots \\ d_{nz} \end{Bmatrix} = \begin{Bmatrix} F_{1x} \\ F_{1y} \\ \dots \\ F_{nz} \end{Bmatrix}$$

where the F and d indicate the nodal force and displacement respectively. The subscripts to the right of F and d denote the node and the direction of force or displacement, respectively. For instance, d_{1x} indicates the displacement at node 1 in the x direction.

For the truss, the matrix analysis is carried out by calculating the stiffness of all elements one by one, and figuring out the loads which are applied in the element by the displacement of the nodes. The combination force generated by every single element to a nodal point must be equal to the external loads at that point. To establish the mathematical equations of the truss system, it is essential to figure out the relation of the force to displacement at every single end of the element.

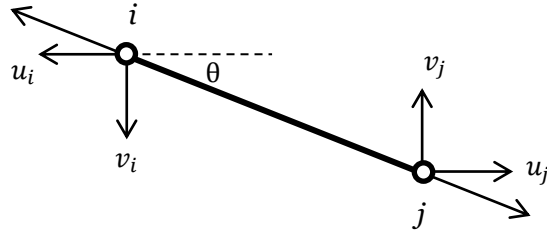


Figure 22 An element of truss

With the parameters shown in **Figure 22**, it is possible to define an elongation vector δ which is resolved in directions along and transverse to the element (Roylance, 2001):

$$\begin{aligned}\delta &= (u_j \cos \theta + v_j \sin \theta) - (u_i \cos \theta + v_i \sin \theta) \\ &= [-\cos \theta \quad -\sin \theta \quad \cos \theta \quad \sin \theta] \begin{Bmatrix} u_i \\ v_i \\ u_j \\ v_j \end{Bmatrix}\end{aligned}$$

The axial force P accompanied with the vector δ can be worked out by Hooke's law:

$$P = (AE/L)\delta$$

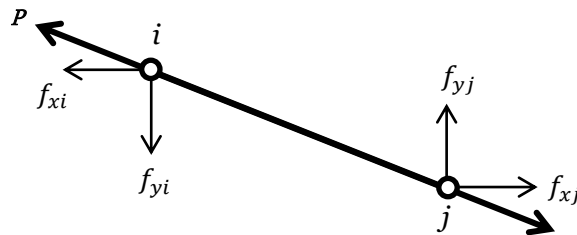


Figure 23 Forces at two ends of an element of truss

Hence, with the parameters defined in **Figure 23**, it is possible to generate the mathematical equations of overall axial force as (Roylance, 2001):

$$\begin{aligned}
\begin{Bmatrix} f_{xi} \\ f_{yi} \\ f_{xj} \\ f_{yj} \end{Bmatrix} &= \begin{Bmatrix} -\cos \theta \\ -\sin \theta \\ \cos \theta \\ \sin \theta \end{Bmatrix} P = \begin{Bmatrix} -\cos \theta \\ -\sin \theta \\ \cos \theta \\ \sin \theta \end{Bmatrix} \left(\frac{AE}{L} \right) \delta \\
&= \begin{Bmatrix} -\cos \theta \\ -\sin \theta \\ \cos \theta \\ \sin \theta \end{Bmatrix} \left(\frac{AE}{L} \right) [-\cos \theta \quad -\sin \theta \quad \cos \theta \quad \sin \theta] \begin{Bmatrix} u_i \\ v_i \\ u_j \\ v_j \end{Bmatrix} \\
&= \left(\frac{AE}{L} \right) \begin{bmatrix} \cos^2 \theta & \cos \theta \sin \theta & -\cos^2 \theta & -\cos \theta \sin \theta \\ \cos \theta \sin \theta & \sin^2 \theta & -\cos \theta \sin \theta & -\sin^2 \theta \\ -\cos^2 \theta & -\cos \theta \sin \theta & \cos^2 \theta & \cos \theta \sin \theta \\ -\cos \theta \sin \theta & -\sin^2 \theta & \cos \theta \sin \theta & \sin^2 \theta \end{bmatrix} \begin{Bmatrix} u_i \\ v_i \\ u_j \\ v_j \end{Bmatrix}
\end{aligned}$$

For the general 2D or 3D stress analysis problems, they more complicated than the truss element problem. An approximate connection between nodal forces and displacements are generated so as to establish an element stiffness matrix. The Hookean constitutive equations are often adopted to change the stress in the equilibrium equation to the strain. Moreover, the kinematic equations are employed to change the strain to the displacement.

The normal and shear stresses on a 3D element are illustrated in Figure 24. The relationship between the stress $\{\sigma\}$ and strain $\{\varepsilon\}$ for an isotropic material can be written as (Langer, 2002):

$$\{\sigma\} = [D]\{\varepsilon\}$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_x \\ \tau_y \\ \tau_z \end{Bmatrix} = \frac{E}{(1+\nu)(1-\nu)} \times \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ & 1-\nu & \nu & 0 & 0 & 0 \\ & & 1-\nu & 0 & 0 & 0 \\ & & & (1-2\nu)/2 & 0 & 0 \\ & & & & (1-2\nu)/2 & 0 \\ & & & & & (1-2\nu)/2 \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix}$$

where $[D]$ is called the constitutive matrix, σ indicates the normal stress, τ indicates the shear stress, E is defined as the modulus of elasticity, ν is the Poisson's ratio, ε denotes the normal strain, γ is defined as the shear strain, and the subscripts x, y, z indicate the direction.

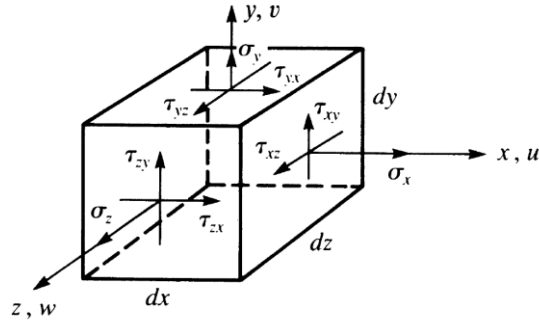


Figure 24 normal and shear stresses on a 3D element (Langer, 2002)

After the Stress/Strain relationship is defined, the element stiffness matrix and equations can be derived for the 3D element.

In order to make the numerical equation suitable for the computer to process, the stress analysis problem can be written as follows (Roylance, 2001):

$$\int_A f(x, y) dA \approx \sum_l f(x_l, y_l) w_l$$

The location of the sampling point x_l, y_l and the corresponding weight w_l are obtained by standard sub-routines, which plot the elements into appropriate shapes, decide the integration point and weight in the altered coordinate frame, and then return the result to the previous frame.

The processor cycles through each element to produce the matrix, assembles all matrices into the accurate positions in the global matrix, and solves the mathematical equations to figure out the displacement and force data.

3.3.2.5 Step 5: Data analysis and post-processing

The post-processor visualises and displays coloured contours demonstrate results generated by the FEA solver. Stresses, strains, and deformations are plotted and observed to find how the model responded to the given loading conditions. Based on the analysis, adjustments may be carried out to the model to improve its performance. In multi-disciplinary and multi-objective structural optimisation, the FEA result is delivered to the optimiser, which will figure out a set of Pareto front solutions for the decision maker.

The FEA technique will be applied and demonstrated in Chapter 6 CASE STUDIES AND VALIDATION.

3.3.3 DOE and Algorithm Key Technique

3.3.3.1 Design of Experiment

Design of Experiments (DOE) approach was originally developed around a century ago in Britain by Ronald Fisher (Vairis, 2009). The DOE approach is defined as one or several tests where the input variables are changed, in order to find relevant factors which result in changes of the response. The DOE approach can not only shorten the time but also enhance the possibility to find a better solution which is not expected in the designer's experience (Roy, 2008).

The DOE approach aims to maximise the information obtained from experimental data by using a smart positioning of points in the space. The DOE is a powerful methodology to design and analyse experiments, eliminate surplus individuals and reduce the time and resources to conduct experiments. An optimal distribution of input points determined with a DOE method will collect the most relevant information with the minimum effort. The DOE technique is vital for studying the behaviour of the objective function and identifying crucial factors (Vairis, 2009). Hence, this study adopts the DOE approach in the framework development.

The DOE technique generates a set of points to define a meta-model by carrying out explorations of the design space. In addition, it figures out a proper initial point for an optimisation algorithm. There are mainly 5 types of DOE techniques (Enginsoft, 2011):

- a) Customer set. This type of DOE technique is generated by the user;
- b) Exploration DOE techniques: such as Random Sequence, Sobol, and Latin Hypercube. Those DOE techniques are suitable for collecting basic information on the problem. They rule out subjective bias, enable worthy sampling of a configuration space, and perform efficiently at finding a good initial point for an optimisation;

- c) Factorial DOE techniques: such as Full Factorial, Cubic Face Centered, and Latin Square. They are crucial for conducting mathematical studies and finding critical relations among variables;
- d) Orthogonal DOE techniques: such as Taguchi Matrix, and Plackett Burman. They are valuable to find major effects or to control noise factors;
- e) Other DOE techniques. They may be suitable for some specific tasks when other techniques fail to work.

Latin hypercube sampling (LHS) is a mathematics technique for generating a sample of feasible sets of variables from a multi-dimensional distribution. LHS “preserves marginal probability distributions for each variable simulated, while matching target correlations between variables” (Huntington, 1998).

The LHS aims to sample an N-dimensional matrix with M points. For instance, we can arrange an experiment with 4 aircrafts for 2 functional variables test, using LHS techniques. In this case, N=2, M=4, and one feasible LH matrix is:

$$P = \begin{bmatrix} 1 & 3 & 2 & 4 \\ 2 & 1 & 4 & 3 \end{bmatrix}^T$$

The corresponding samples are showed in Figure 25.

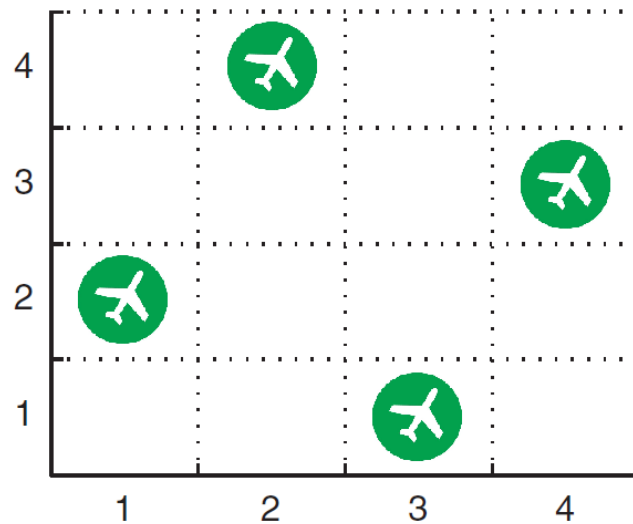


Figure 25 Latin hypercube sampling in 2-dimensional space

These DOE techniques are investigated in the questionnaire and interview which are presented in Chapter 4, and it is found that a good starting point is always the most important factor in structural optimisation. Therefore the exploration DOE techniques are adopted in this study. Among the exploration DOE techniques, the Latin hypercube is voted to be the most popular one by questionnaire respondents. Hence the Latin hypercube is employed in the case studies.

3.3.3.2 Optimisation Algorithms

The algorithmic approach is widely used for dealing with “increasing complexity, real life design requirements, increasing designer confidence, hybrid and other” (Roy, 2008).

Multi-objective Evolutionary Algorithms (MOEAs) are increasingly popular to optimise numerical aerospace engineering problems. The MOEAs deliver outstanding performance on the robustness and simplicity of solutions. They are also easy to parallelise and hybridise (Arias-Montano, 2012).

In aerospace engineering practise, MOEAs are commonly recognised as an alternative numerical optimisation technique due to their ease of use and efficiency (Arias-Montano, 2012). Typical MOEAs are listed in Figure 26 (Coello, 2006). They can be classified into two generations. The first generation, developed very early, includes NSGA, NPGA and MOGA. It is widely believed that MOGA is the best algorithm in the first generation, while NSGA should be avoided due to its inefficiency (Coello, 2006). The second generation of MOEAs, including SPEA, SPEA2, PAES and NSGA-II, performs better in efficiency. In particular, the NSGA-II does not use an external memory as the other MOEAs do (Coello, 2006). According to a study based on publications and real-world application problems, both the MOGA and NSGA-II are the most popular algorithm adopted in aircraft optimisation (Arias-Montano, 2012). Furthermore, considering the poll result from the questionnaire in chapter 4, it is determined to employ NSGA-II in this study.

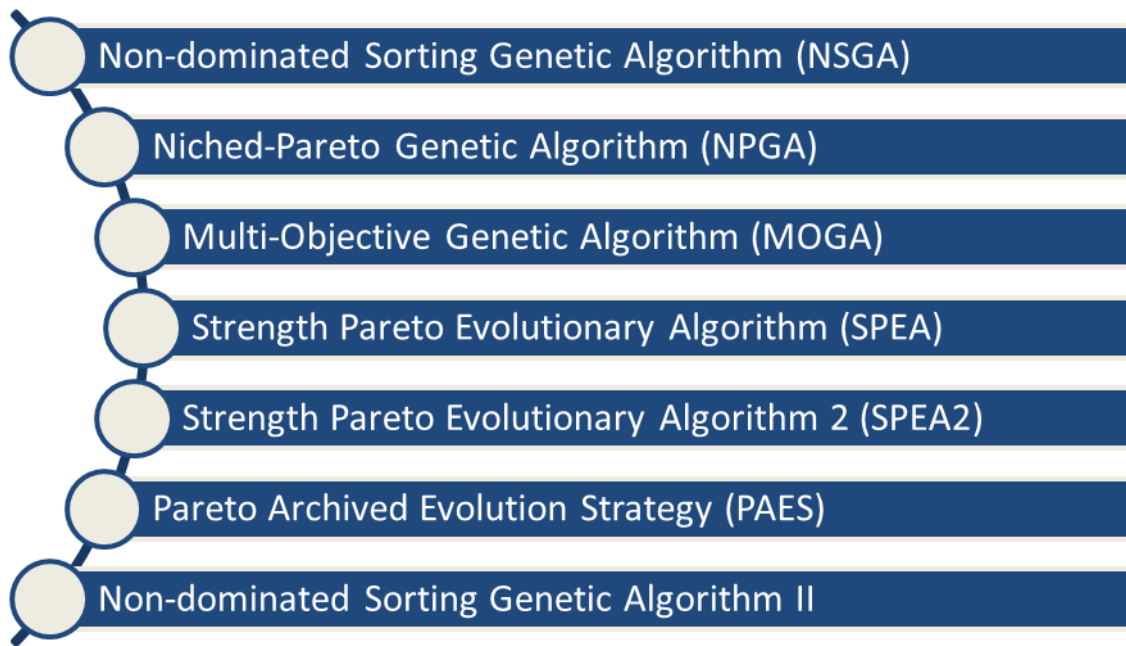


Figure 26 Common Multi-objective Evolutionary Algorithms (Coello, 2006)

Most of the parameter optimisation problems are multi-objective involving different types of variables. The selection of fitness values needs an iterative procedure. The calculation of fitness function is usually expensive in parameter optimisation. This problem can be reduced by developing acceptable surrogates which are generated with simulation results. However, this is extremely challenging when there are numerous variables. Usually, the parameter optimisation adopts hybrid Genetic Algorithms to find candidates, and then a local exploration to work out the optimum. The shape optimisation is featured in extra large amounts of variables and costly calculation. Hence, the parallel collaboration of the GA with game theory (Periaux, 2001) is critical in this case (Roy, 2008).

3.4 Summary

This chapter introduces the adopted research strategy in this study. In general, there are four phases to carry out this research. The first stage aims to develop a clear understanding of this research. A wide range literature review is conducted to acquire background knowledge. The second step is to collect the problems and information related to the structural optimisation through questionnaire and semi-structured interview. In the third phase, the structural optimisation is classified according to component, and typical constraints and objectives are summarised. Then the framework is developed. The validation phase aims to validate the framework by conducting three case studies. The case studies will also be reviewed by experts through questionnaire or interview. Finally the recommendations are presented.

In addition, the methodology is also presented in this chapter, including the key techniques of FEA, DOE and optimisation.

4 DATA COLLECTION AND ANALYSIS

4.1 Introduction

In order to acquire sufficient information from industry and experts, questionnaires and interviews are conducted in this study. The questionnaire contains general questions while the interviews concentrate on specific questions. The questionnaire aims to get feedback from as many relevant engineers and researchers as possible while the interview targets at the selected experts with knowledge of structural design or optimisation.

4.2 Data Collection

4.2.1 Questionnaire Development

4.2.1.1 Questionnaire structures

The questionnaire consists of four parts.

The first part is about the personal information and work background. In order to get a picture of the commonly used software to determine which software would be adopted to carry out this study, the CAD, FEA and optimisation tools are also investigated in this part.

Part II focuses mainly on how to define and set up the optimisation. Questions about the nature of the typical optimisation problems, such as the work flow, objectives, variables and constraint, are asked in this part.

Furthermore, the third part is designed to learn what DOE techniques and algorithms are deployed to solve the optimisation problems.

Finally, questions regarding the challenges and suggestion are presented to ensure this study could be valuable and useful.

The full version of questionnaire can be found in Appendix A.

4.2.1.2 Questionnaire forms

With the intention to maximise the responses of questionnaire, two forms are created to hand out. The first one is traditional hard copy version, which is

handed out in the workshop or meeting. Due to the limitation of attendees of the workshop or meeting, it is necessary to develop a second way to collect questionnaire responses online. Therefore an online questionnaire is employed (as shown in Figure 27). The questions are exactly the same to the paper version, though the Chinese translation is present to make it accessible for respondents from China.

Structural Design Optimisation QUESTIONNAIRE

INTRODUCTION

This questionnaire is part of Study of Optimisation Strategies for Aircraft Structural Design, an MSc by research project.

Nowadays, engineers who want to optimise designs still need to spend a lot of time with learning and deciding on optimisation models, parameters, constraints etc. and how to combine simulation software best with the various optimisation algorithms. The work of engineers could become more efficient if they had practical guidelines that provided recommendations for a more systematic approach to optimisation of aerospace structures. This study addresses this general problem while focussing on applications of typical design tools such as CAD and FEA software.

The aim of this research project is to classify and summarize typical objectives and constraints in aircraft structural design optimisation, analyse and develop general workflows and approaches for various single, multi-objective and multi-disciplinary optimisation problems in this domain.

By completing this questionnaire you agree that this data can be used and processed for the legitimate purposes of this study in accordance with the requirements of the Data Protection Act 1998.

It will take about 10 minutes to complete. A soft copy of this thesis could be sent to you on request.

[Continue »](#)

Figure 27 Online questionnaire

Structural Design Optimisation QUESTIONNAIRE

INTRODUCTION

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By completing this questionnaire you agree that this data can be used and processed for the legitimate purposes of this study in accordance with the requirements of the Data Protection Act 1998.

It will take about 10 minutes to complete. A soft copy of this thesis could be sent to you on request.

QUESTIONS

1. Which field do you work in?
☐ Aerospace ☐ Automotive ☐ Maritime ☐ Other

2. Which software is used to design structures in your company?
☐ CATIA ☐ HyperMesh ☐ SolidWorks ☐ Iges

3. Which software is used to do structural analysis in your company?
☐ Ansys ☐ Abaqus ☐ Nastran ☐ Patran

4. Which software is used to do optimisation in your company?
☐ HyperMesh ☐ OptiStruct ☐ Isight ☐ Dymola

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Figure 28 Hardcopy Questionnaire

The interview consists of two parts as demonstrated in Figure 29. The first part is general questions, including optimisation procedure, fitness function, optimisation approaches and convergence analysis in FEA. The second part is specific questions. Each expert has their own research field and interest, so tailored questions could make the most of the interview. In addition, there may be more questions brought up in the first part of interview, they could be added into the specific part.

**Structural Design Optimisation
INTERVIEW OUTLINE**

Name: _____ Email: _____
 Title: _____ Date: _____
 Company: _____

GENERAL QUESTIONS

- 1) What is your first set of 5 problems you did when you start an optimisation project?
- 2) What do you do if you do not have an explicit fitness function?
- 3) How many fitness evaluations are you typically allowed to use?
- 4) How do you shorten the time spent on the multistate convergence analysis in FEA?

5) How do you shorten the time spent on the evaluation of the fitness?

6) How to select the approach from evolutionary, classical and hybrid approaches?

7) How do you select the optimisation software?

8) Do you follow any best practice when you start representing a problem?

SPECIFIC QUESTIONS

-
-
-
-
-
-

Figure 29 Interview Outline

The interview is conducted with four experts from the aerospace industry: Alex Quirk and Jacquelyn Quirk from Altair Engineering UK, and Weiping Li, Jian Chen from COMAC. Their information can be found in Table 2.

Table 2 Interviewee information

NAME	POSITION	COMPANY	EXPERIENCE
Alex Quirk	Project Engineer	Altair UK	composite and metallic analysis and optimisation of aerospace structures using numerical methods and finite element analysis.
Jacquelyn Quirk	Academic Liaison	Altair UK	the Airbus A350 virtual full-scale test model of the outer wing box
Weiping Li	Project Engineer	COMAC	Structures stress analysis of the ARJ21 and C919
Jian Chen	Project Engineer	COMAC	Material analysis of the ARJ21;Fuselage design of the C919

4.3 Data Analysis

4.3.1 Questionnaire Analysis and Discussion

4.3.1.1 Respondent work background

It is very important to select certain respondents to ensure the quality and diversity of answers. There are 15 effective responses returned from experts in various fields. As shown in Figure 30, most of the respondents are engineers from aerospace industries, and researchers in academic institutions.

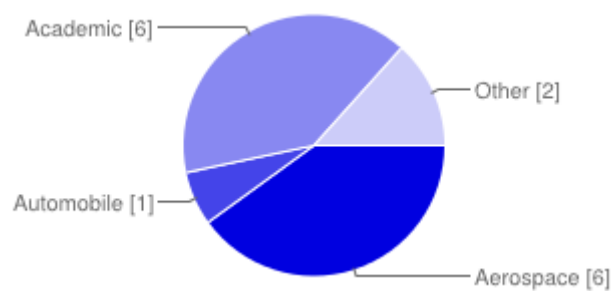


Figure 30 Questionnaire respondents distribution

For these respondents, CATIA, Hyperworks and Modefrontier are the most popular CAD, FEA and optimisation tools respectively.

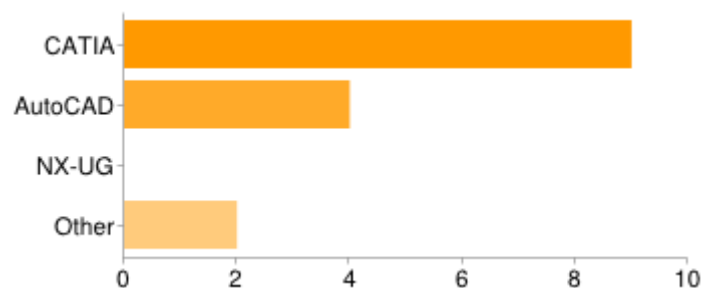


Figure 31 CAD tools distribution

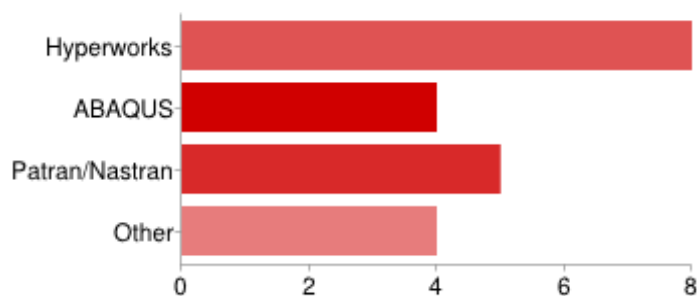


Figure 32 FEA tools distribution

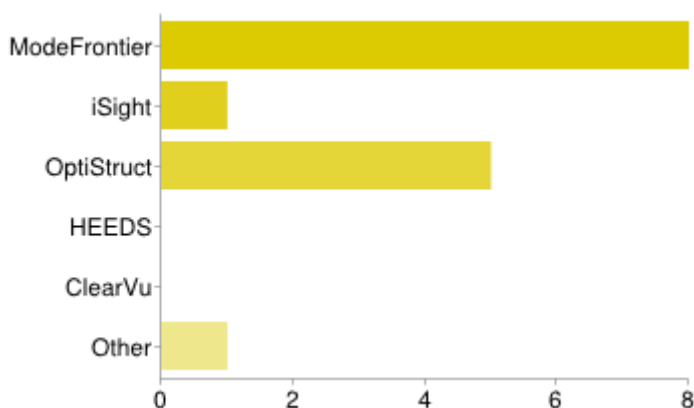


Figure 33 Optimisation tools distribution

Regarding the optimisation module built in the CAD/FEA tools, respondents have different preferences. The CAD and FEA tools are developing very fast and some advanced CAD and FEA software could perform optimisation functions. Therefore it is investigated in this questionnaire to find out whether the optimisation functions integrated in CAD/FEA tools are practical and useful. Around 33% respondents claim they use built-in optimisation feature in the CAD/FEA tools. Due to the integration of optimisation modules and design modules, they think it boosts the efficiency. Optimisation toolboxes in Matlab and Optistruct in Hyperworks are examples of this kind. On the other hand, the drawbacks of the integrated optimisation module are also pointed out by many respondents. Since the integrated optimisation module usually has few

algorithms, and takes long time to find the optimum. Some respondents even doubt the accuracy of the results.

4.3.1.2 Define and set up the optimisation

There are various answers to *what workflows (steps) do you set to carry out the optimisation*, however, they can be abstracted as one common route as shown in Figure 34.

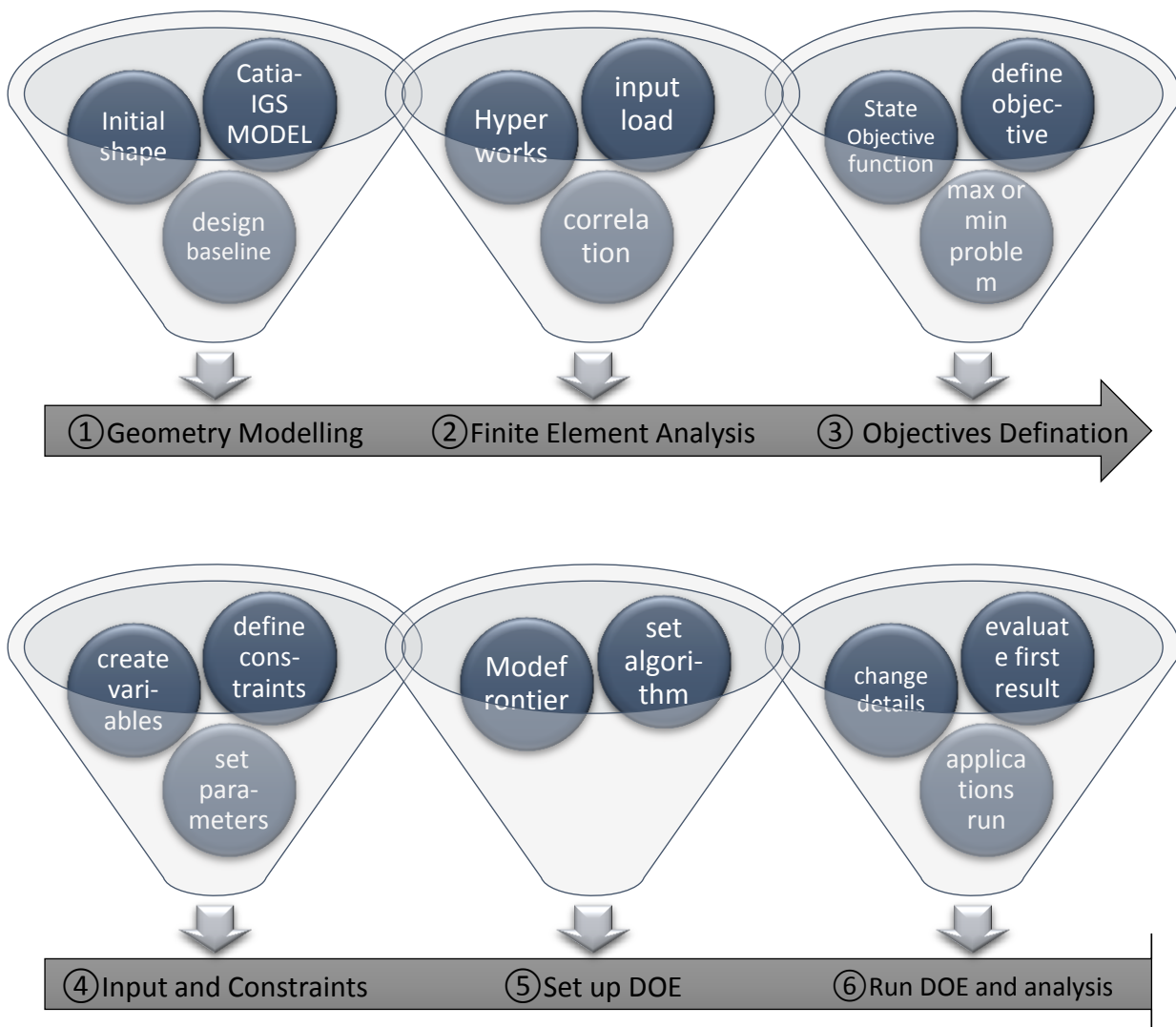


Figure 34 Workflow abstract from responses quote

For a typical optimisation problem, it usually involves more than 5 input parameters (see Figure 35) and 1 to 2 objectives (see Figure 36). Therefore the large number of variables is believed to be a key factor to effect the optimisation time, in some cases it should be considered to compare all variables' effects on the result and define the most important variables to reduce the number of variables. Moreover, single objective and multi-objective optimisation are both common in industries and researches.

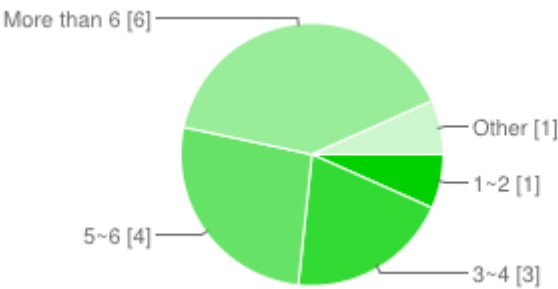


Figure 35 Number of input parameters

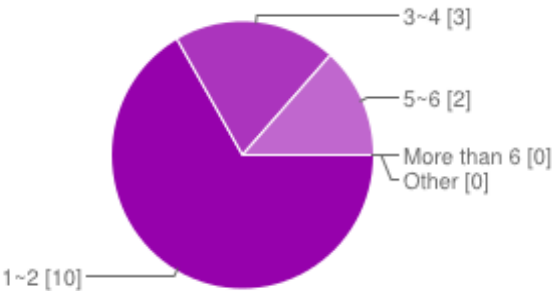


Figure 36 Number of objectives

As can be seen from Figure 37, the constraints vary with different problems.

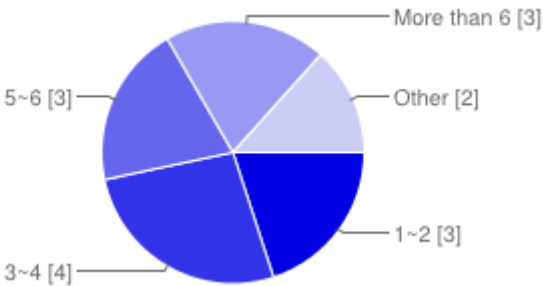


Figure 37 Number of constraints

4.3.1.3 DOE techniques and algorithms

As shown in Figure 38, among several optional DOE techniques, the Latin Hypercube is the most popular one.

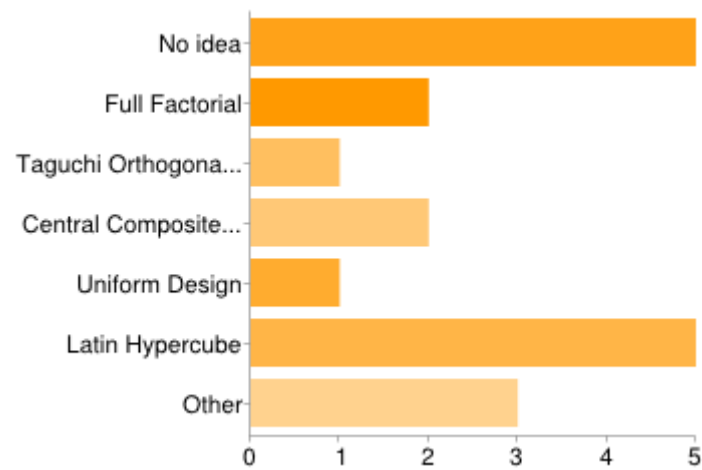


Figure 38 Popular DOE techniques

It is quite interesting to find how engineers and academics researchers behave differently on DOE techniques. Table 3 indicates a significant portion of aerospace engineers do not know how to use the DOE technique, while academics researchers show a high awareness about it.

Table 3 Knowledge comparison on DOE techniques

	Total number	Number of “No idea” about the DOE	Rate of “No idea” about the DOE
Engineers in aerospace	6	3	50.0%
Engineers in other fields	3	1	33.3%
Academics researchers	6	1	16.7%

NSGA-II, MOPSO, HYBRID and evolution strategy are widely used as optimisation algorithms, although other algorithms are also very popular (see Figure 39).



Figure 39 Popular algorithms

Regarding the principle of selecting algorithms, two kinds of answers were given. Majority respondents would leave it for the optimisation software to decide or just use the built-in algorithms. In this case they do not have to learn about the algorithms or mathematics theory, which makes the optimisation more accessible for those less skilled or experienced engineers. However, the algorithms which are chosen by software itself may not be the best technique to find the optimum in a given time. Only a few respondents point out they use their experience and knowledge to decide the algorithms, based on the input, output and objectives. This has a high requirement of the ability of the engineers.

The main difficulties and challenges in structural optimisation problems are also collected from the questionnaire. This is designated to find which part of optimisation should be concentrated in this study when defining the objectives so the approach developed can be useful and practical.

It is also interesting to learn about what people would expect from this study. For most of the respondents, they would like to see a framework that helps them to carry out an optimisation. The demand for the existing applications is also mentioned. In addition, some respondents would like to read the comparison of different optimisation techniques. These demands should be considered and satisfied in this study.

4.4 Summary

This chapter introduces the development and content of the questionnaire and interview, and shows how the questionnaire and interview are conducted. Then the results from the questionnaire and interview are analysed.

The questionnaire consists of four parts. The first part is about the personal information and work background. Part II focuses mainly on how to define and set up the optimisation. The third part is designed to learn what DOE techniques and algorithms are deployed to solve the optimisation problems. Finally, questions regarding the challenges and suggestion are presented. Due to the insufficient algorithms, long operation time and unreliable results, the integrated optimisation module in the CAD/FEA software is not popular. In some occasions it is advised to compare all variables' effects on the result and define the most important variables to reduce the number of variables.

Most of the respondents of the questionnaire are engineers from aerospace companies, and researchers in academic institutions. CATIA, Hyperworks and Modefrontier are the most popular CAD, FEA and optimisation tools respectively. The Latin Hypercube is the most popular DOE techniques, while NSGA-II, MOPSO, HYBRID and evolution strategy are widely used as optimisation algorithms.

The interview consists of two parts. The first part is general questions, including optimisation procedure, fitness function, optimisation approaches and convergence analysis in FEA. The second part is specific questions.

It can be learnt from the interview that most of the product cost is determined at the concept design stage. The optimisation procedure, typical objective function and manufacturing constraints are discussed.

5 CLASSIFICATION AND FRAMEWORK DEVELOPMENT

5.1 Introduction

It is essential to find and classify typical optimisation applications for each aircraft component respectively. Different component has distinct work condition and requirement, so the objectives and constraints are unique. For some applications, additional criteria apart from structure considerations (such as aerodynamics performance or system requirements) should be considered, which makes it a multi-discipline optimisation problem. This can be done by analysing information from the case study, literature review, questionnaire and interviews. This list of optimisation applications can help engineers to find what should be taken into account when they design the structures.

Then the framework for aircraft structural optimisation is developed.

5.2 Airframe Optimisation Classification

Four components are analysed in this study. They are fuselage component, wing component, landing gear component and pylon component, as illustrated in Figure 40.

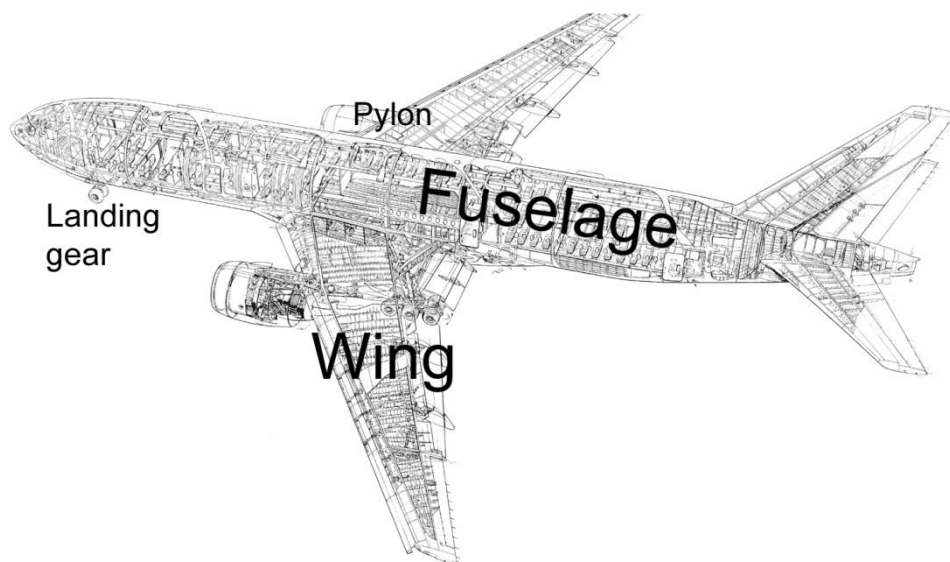


Figure 40 Analysed Components

5.2.1 Fuselage optimisation analysis

According to Van, there are three main disciplines that fuselage design should consider: structural, acoustics and thermal (Van, 2007).

The most important discipline is structural criteria, including the skin and stringer buckling, allowable tensile and compressive stresses in the skin (or stringer) material.

Acoustical insulation of the fuselage component is achieved using interior panels and insulation blankets. The frequency and structural details of the fuselage will decide the acoustical insulation performance. Besides, viscoelastic layers can be applied to skin and interior panels to make greater transmission loss. The interior panels are deployed on the inner surface of the fuselage. The insulation blankets are installed between the frames.

Thermal insulation of the fuselage component is also accomplished with insulation blankets. The single, unstiffened skin of the fuselage influences the thermal insulation performance. The insulation blankets have the same thickness to the height of the frames.

Design constraints in fuselage optimisation usually include the buckling, the tensile stress, the tensile stress criteria of the skin and stringers, and the Euler buckling criteria of the stringers. Moreover, typical design objectives are: the maximisation of the temperature gap between the inner and outer fuselage skins, the maximisation of the global acoustic transmission loss, the minimisation of the structural weight of the fuselage component, the minimisation of the whole weight of the fuselage component including the structure, blanket and interior panels (Van, 2007).

5.2.2 Wing optimisation analysis

5.2.2.1 Related Disciplines

There are two main disciplines that wing design should consider: mechanics and aerodynamics.

5.2.2.2 Wing Box

The objective of the wing box optimisation is usually to minimise the weight.

According to Schuhmacher, the thickness variable of the skin and the height variable of the stringer are key figures (Schuhmacher, 2002). For each space unit that is separated by adjacent ribs and stringers, the skin elements are defined as an individual design variable. Similarly, the stringers are also divided by the space unit to define another set of design variables. Due to the low effects on the internal load flow and overall stiffness, the size of the inner rib and the spar stiffener can be screened. Every single component is sub-divided once more into the upper- and lower- panels, front- and rear- spars, skin and stringers. Therefore the optimisation variables are: Upper skin, Lower skin, Upper stringers, Lower stringers, Front spar web, Front spar stiffener, rear spar web and rear spar stiffener in each space unit.

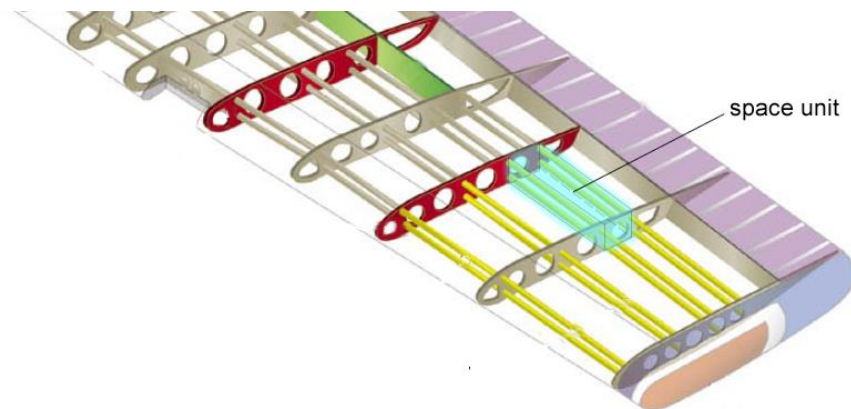


Figure 41 The definition of space unit, picture modified from <http://www.nomenclatur.com/airplane-wing-part-diagram-terminology.html>

In the overall design phase, 3 main constraints should be taken into account: the maximum displacement of the wing tip, the maximum allowable von Mises stress, and minimum buckling (Ledermann, 2006).

The first constraint is the structure compliance, which can be replaced by its reverse: the stiffness. The maximum displacement or deformation of the wing should be controlled so that the flaps, actuators can function well.

Then the stress constraint is set. Non-plastic deformation is guaranteed by a further constraint similar to the stiffness constraint. The acceptable Von Mises stress of the whole wing component is limited by the stress performance of the material. This overall constraint can prevent the plastic deformation.

Finally, the buckling constraints function (Wing buckling factor BF_0) should be created for the buckling field, which is defined as the surface separated by the neighbouring ribs and spars.

Evolutionary algorithms (EA) are recommended by Ledermann because they allow dealing with discrete search spaces objective functions.

However, in the detail design phase, different parts will have varied constraints. Fatigue constraints should be given to parts such as the lower skin panels, main joints, front spar web near the pylon and rear spar web near the landing gear (Schuhmacher, 2002).

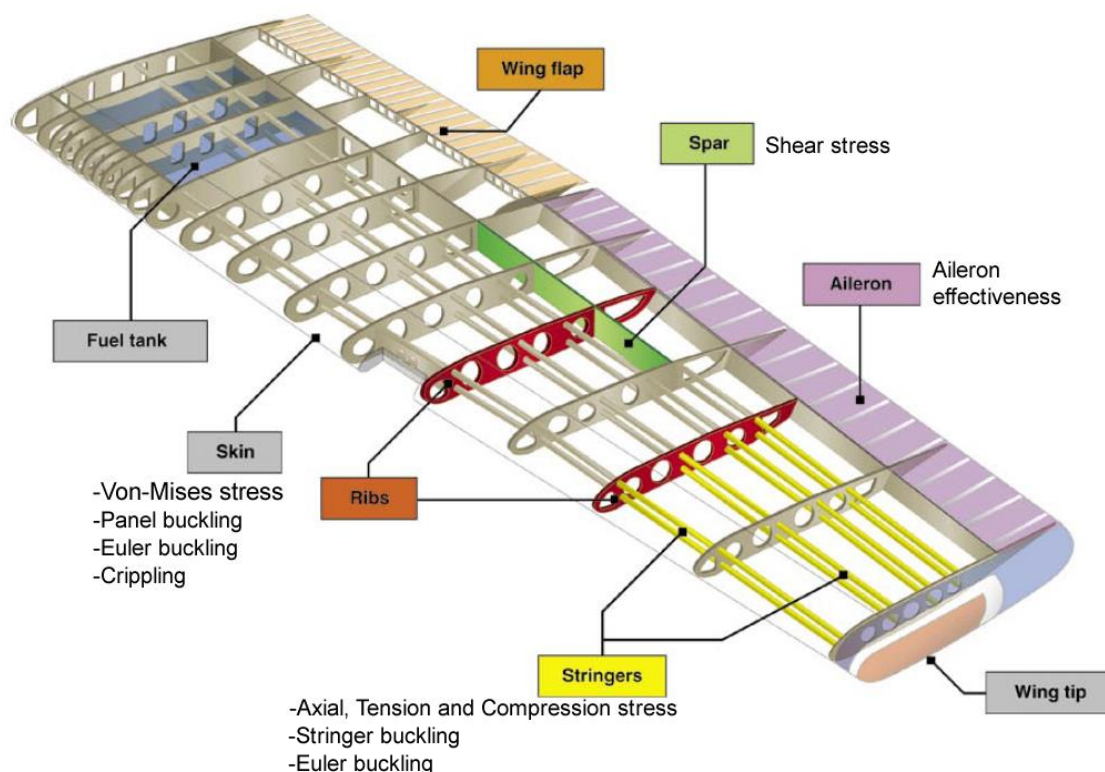


Figure 42 Typical constraints in the wing design, picture modified from <http://www.nomenclaturu.com/airplane-wing-part-diagram-terminology.html>

5.2.3 Landing gear optimisation analysis

There are two types of optimisation problems in the landing gear design (Alex Quirk, interview):

- a) Torsion links: The torsion link is one of the key factors which affect the performance of the landing gear due to the frequent braking and turning while taxiing, therefore the stress performance and manufacturing constraints should be highlighted.
- b) Lugs: The lug integrated with the outer cylinder is also a factor to affect the fatigue performance during taxiing.

5.2.4 Pylon optimisation analysis

The pylon structure is composed of six vertical beams, three pairs of tension rods, three horizontal beams and one transitional beam, as shown in Figure 43. The pylon structure will be linked to the main beam of airplane by six vertical beams. The two loading points are located on the transitional beam.

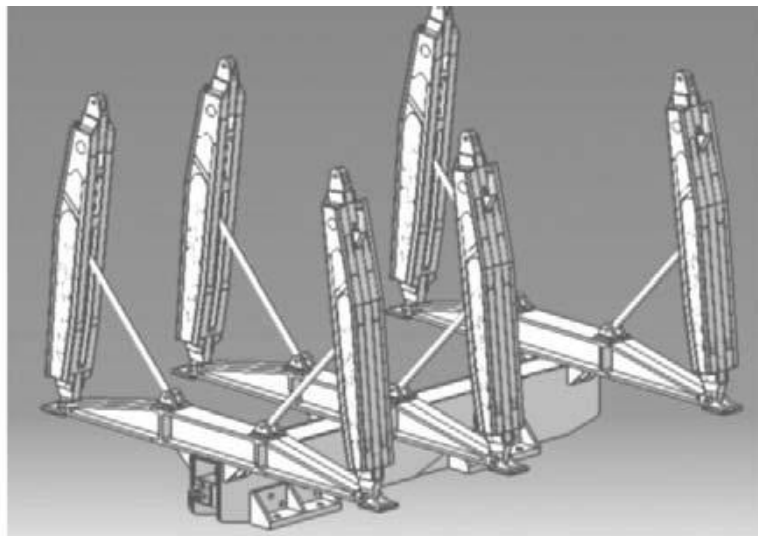


Figure 43 The Pylon structures(Weigang 2007)

The design variables are the dimensions of the cross-section of ten components. They are three pairs of tension rods, three horizontal beams and one transitional beam. The objectives are minimizing the mass and displacement. The constraints are strength constraint and the limits of design variables.

5.2.5 Typical objectives and constraints

As analysed in the previous section, and discussed in the questionnaire and interview analysis in the chapter 4, typical objectives and constraints can be summarised in Table 4.

Table 4 Typical objectives and constraints

Mass(Weight)	Volume	Static Displacement
Static Compliance	Buckling	Static Stress, Strain, Forces
Frequency		

Typical Objectives and Constraints set in a topology optimisation problem are listed in Table 5.

Table 5 Typical Objectives and Constraints set in topology optimisation

Objectives(Max or Min)	Constraints
compliance	volume / mass
volume / mass	displacements
frequency	volume / mass
volume / mass	frequencies
compliance and frequencies	volume / mass
volume/ mass	Stress

5.3 Structural Optimisation Framework

5.3.1 Framework introduction

It is essential to define the design and optimisation problem before the determination of the approach. Hence the first stage will be the problem initialisation and concept design phase. Then two approaches are developed individually corresponding to different types of optimisation problems.

The framework also contains several links to some recommendation in chapter 7, which enables the seamless connection between the framework and recommendation.

5.3.2 Problem initialisation and concept design

The input of the design and optimisation should be initialised by defining specifications and requirements. For different companies and industries, there are distinct pre-defined specifications and requirements. In aerospace industry, the airworthiness requirements are particularly important. The design space is also defined to make sure the design will not interfere with other parts or components. Then the baseline model is created to provide an initial design for optimisation. The baseline design shall consider:

- a) Overall Configuration Arrangement;
- b) Neighbouring system, and surrounding components structure;
- d) Airworthiness specifications and regulations.

Based on those specifications, requirements and baseline design, the initial optimisation objectives and constraints can be identified.

Subsequently, the initial optimisation objectives are analysed to decide which could be transformed into constraints. This will be discussed in the recommendation section in chapter 7.

Once the number of objectives is confirmed, the optimisation can be identified as a single objective, multi-objective or many-objective problem. Recommendation for the many-objective problem can be found in in chapter 7.

For the multi-objective problem, the DOE and algorithmic approach will be employed.

However, the approach for the single objective problem needs to be determined based on further analysis. The number of main disciplines is vital to decide if general approach or the DOE and algorithmic approach should be adopted. The problem with more than one discipline is defined as multi-disciplinary optimisation, in which the DOE and algorithmic approach is used. However, the general approach is applied if the structural discipline is the only one that is involved in the optimisation.

5.3.3 General approach

The general approach is widely used in engineering practice, and can be divided into two phases: the preliminary design phase and the detail design phase (Arias-Montano, 2012). However, not all of them are compulsory. Some phase can be skipped or simplified, depending on the time and cost limitation. This will be discussed in the recommendation chapter.

In the preliminary design phase, topology optimisation is applied to optimise the material distribution. The baseline design is imported to the pre-processor to define the designable space. Meshing is applied to the designable space and non-designable space. Then the mechanical connections are created. Loads and boundary conditions, which are defined in the concept design phase, are applied to the model. Optimisation responses are set up to create the optimisation objectives (function) and constraints (function). To make the topology optimisation more practical and useful, the manufacturing constraints are placed additionally. Then the FEA model is ready to run in the optimiser or solver.

When the topology optimisation is concluded, the result is visualised in the post-processor and the performance is analysed. The optimum will result in a new geometry, which the modification of the CAD model is based on.

After the preliminary design phase, the shape and sizing optimisation will be applied in the detail design phase. The FEA model is set up following similar

procedure in the topology optimisation. However, for the shape optimisation, the domains, volumes and handles should be defined to complete the mesh morphing and perturbations. Then the shapes are assigned to design variables to set up the responses, which will later form the optimisation objectives (function) and constraints (function). Then the optimisation is set up and run in the optimiser or solver.

When the shape and sizing optimisation is finished, the result is shown with the post-processor and the outcome is evaluated. The optimum will be reflected in the new geometry model.

5.3.4 DOE and algorithmic approach

The DOE and algorithmic approach is used for solving multi-objective and multi-disciplinary optimisation problems. The design variables should be initially defined at the beginning of the optimisation. The optimisation will be very time consuming and expensive if there are many design variables. Therefore those initial design variables will be evaluated to decide which are highly relevant to the response surface and which are relatively insignificant that can be ruled out.

Subsequently, the optimisation objective functions and constraint functions are generated. These objective functions and constraint functions are usually based on the response such as the displacement of a specific point.

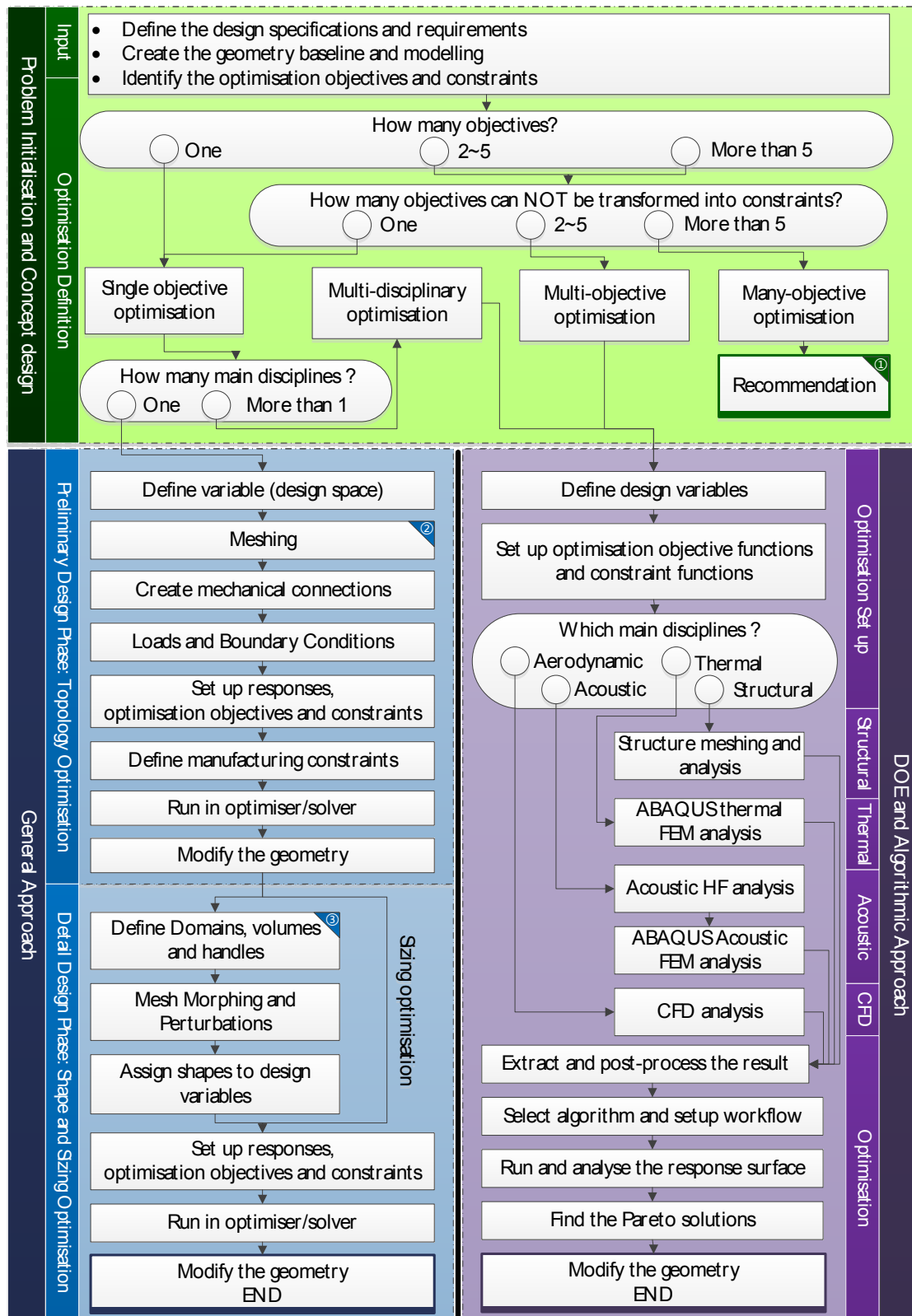
According to relevant literature, there are mainly four types of disciplines that involved in the aircraft structural optimisation: aerodynamic, thermal, acoustic, and structural (Van 2007; Locatelli 2010; Saleem 2008; Schuhmacher 2002). For the multi-disciplinary optimisation, different solvers will be linked and integrated to communicate with the optimiser.

Then the DOE sequence is created to provide a series of combinations of design variables. The optimisation algorithm is also selected to complete the workflow setup. The optimiser will run the solver(s) and calculate the response surface, which is essential for the optimiser to create a simulator. The simulator will replace the solver(s) to produce responses to optimiser. This saves time and reduces cost.

In aerospace engineering practise, the Latin hypercube is typically adopted to create DOE sequence, and the NSGA-II is widely used as the optimisation algorithm.

When the optimisation is completed, the Pareto front can be post-processed. The optimum solutions can be submitted to the decision making team, then the final result can be determined and applied in the geometry.

5.3.5 Framework chart



① refers to recommendation 7.3.1; ② refers to recommendation 7.3.2; ③ refers to recommendation 7.3.3.

Figure 44 Aircraft structural design optimisation framework

5.4 Summary

This chapter analyses four components in airframe structures: the fuselage component, wing component, landing gear component and pylon component. Relevant disciplines, objectives, constraints are summarised and classified.

Then the framework is developed and introduced for the single objective, multi-objective and multi-disciplinary optimisation problem. Two approaches are adopted in this framework: the general approach, as well as the DOE and algorithmic approach. The connections between the framework and the recommendation are also presented.

6 CASE STUDIES AND VALIDATION

6.1 Introduction

Three case studies from aerospace industry are used to demonstrate how the framework works. As discussed in the literature review and framework development, three types of optimisation are commonly conducted in aerospace structural design, which are sizing, shape and topology optimisation respectively. Moreover, there are two approaches developed in the framework, which are general approach, and the DOE & algorithmic approach. The case studies will be conducted to show how to carry out different types of optimisation using distinct approaches following instructions of the framework.

It is discovered in the interview analysis that the topology optimisation in the concept design phase will determine most of the product cost. Hence it is important to choose a case study to carry out the topology optimisation. Considering that most of the topology optimisations in aircraft structural design are single objective problems, the first case study is designed to be a single objective topology optimisation application.

Moreover, as multi-disciplinary and multi-objectives techniques are gradually adopted in solving complicated optimisation, especially in academic research, it is necessary to solve a multi-disciplinary or multi-objectives optimisation problem in this study. Therefore the second case study is decided to be a multi-objectives shape optimisation application.

Furthermore, it is essential to demonstrate how to conduct the optimisation in a full cycle design, including the concept design phase and detail design phase. As obtained from the interview and literature review, it is very common in reality that topology optimisation is conducted at first, followed by the shape or size optimisation to decide the details. Hence the third case study is defined to be a single objective combination optimisation.

6.2 Case Study I

6.2.1 Problem Definition

As described in the introduction, the first case study is designed to be a single objective topology optimisation application. A hinge arm provided by COMAC is selected and optimised in this case.

The hinge arm is a part connects the door and the airframe, see Figure 45.



Figure 45 Position of hinge arm in A320, from
<http://www.flickr.com/photos/irishflyguy/2661527245/in/photostream>

COMAC provides the loads, boundary conditions and the initial design space in the form of CATIA model (as shown in Figure 46). Since the original data and geometry model is strictly commercial and confidential, COMAC modified the input data so that it could be published. However, it does not affect the accuracy of this case study and the validation of framework generated in this study.

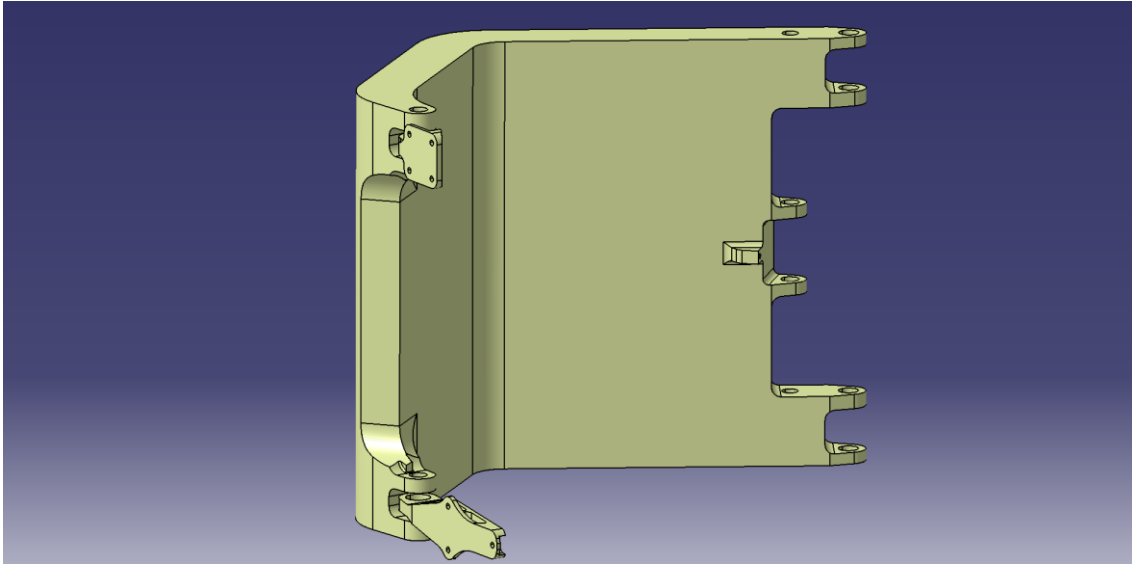


Figure 46 The initial design space of the hinge arm

From the perspectives of the structural engineers, they would like to maximise the strength and stiffness, or equally, minimise the compliance. On the other hand, the weight should be a minimum so the cost can be reduced. Therefore there are 2 initial objectives.

However, according to the framework, it is advised to decrease the number of objectives and transform them into constraints. In this case, the weight objective is converted to constraint, which is the volume fraction. It is set to be more than 30%, which means at least 70% weight could be reduced from the initial baseline design. Hence, the only objective of this optimisation is to minimise the compliance.

Besides, as discussed with experts from COMAC, this case study need to take the structural discipline into account, and no additional disciplines will be involved. Therefore, this case study is defined as a single objective topology optimisation.

6.2.2 Analysis and optimisation

Since this is a single objective optimisation, according to the framework developed in chapter 6, it is advised that general approach should be employed in this case study.

The design space geometry obtained from COMAC is imported into HYPERMESH. It is necessary to clean up the geometry because the imported geometry is not always ready for meshing. The surfaces could be not connected together, redundant or too small to be meshed. Some pre-processor, such as HYPERMESH, provides the tool to clean up the geometry automatically.

Once the geometry is cleaned up, the solid is created based on the surface imported from the baseline CATIA IGES file. The solid is divided and re-organised into two components, one is design space and the other is non-designable. Then the shell mesh (2D) is generated on both components, and converted to tetra mesh (3D). Then the mesh quality is checked.

When meshing is finished, the material AL(Stands for Aluminium) is created and properties are assigned to the design component and non-design component respectively. Although both components are made of the same material, it is essential to create two properties to carry out the topology optimisation.

After that, the loads and boundary conditions are added to the model to apply the load conditions that the hinge arm is subjected to. Different load cases can be defined to represent different loading conditions on the same model. Solver information is also added to tell the solver what kind of analysis is being run, which results to export, etc. As defined jointly with COMAC, the load distribution is indicated in Table 6. Then the FEA setup is completed, as shown in Figure 47.

Table 6 Load distribution in the case study I

	X	Y	Z
Upper Point	-	400N	-
Lower Point	-	1000N	1800N

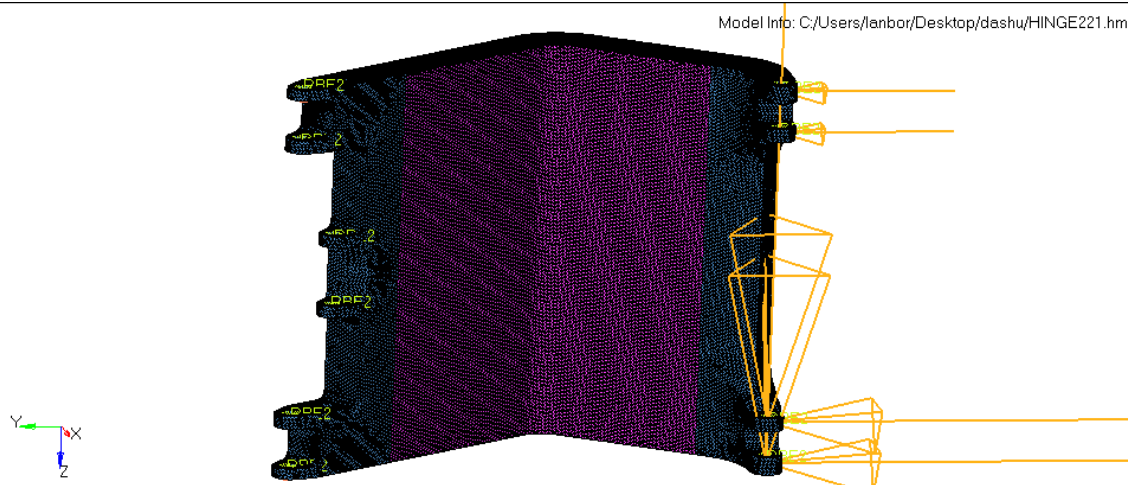


Figure 47 Mesh and FEA setup

Various responses are created to generate the objective (function) or the constraint (function). In this case, the responses VOLUMEFRAC and COMPL are generated, representing the volume fraction and compliance respectively. The optimisation objective OBJECT is defined, based on the response COMPL, to minimise the compliance. Meanwhile, the optimisation constraint CONSTR is created with the response VOLUMEFRAC, ensuring the final optimum is at least 70% lighter than the initial baseline design. For this hinge arm, the manufacturing constraint is the draw direction requirement.

Then the data is submitted to the processor, which is OPTISTRUCT in this case.

6.2.3 Results and comparison

The processor OPTISTRUCT runs and generates the FEA result files. The file with extension .RES includes all the results of displacement through stress, and the file ending with .OUT contains information about the check run before the computation. The .H3D file also contains the results and is post-processed with HYPERVIEW.

The Figure 48 shows the result of this case study with HYPERVIEW. The density distribution is illustrated in Figure 49.

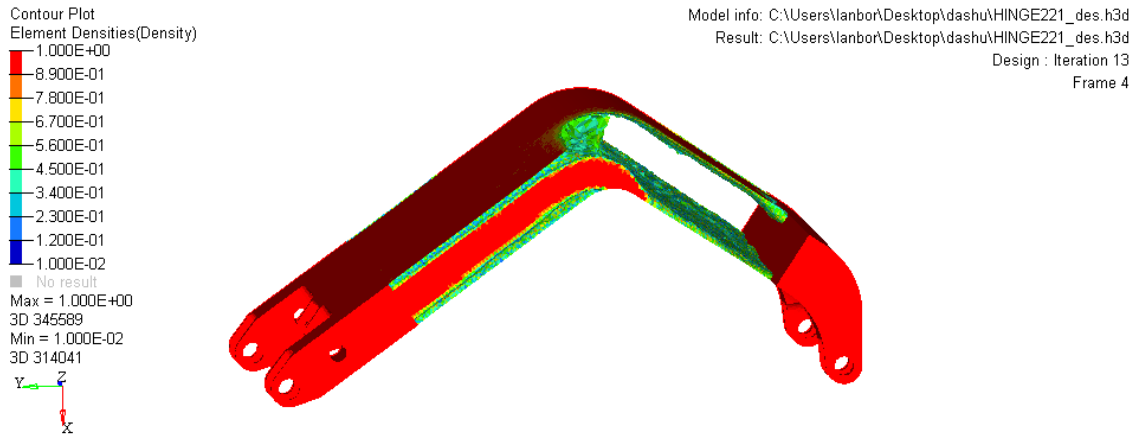


Figure 48 The topology optimisation result

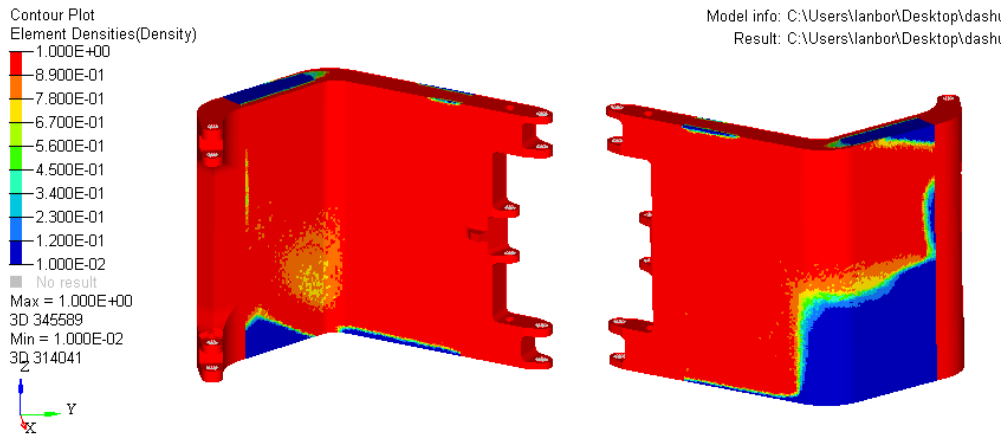


Figure 49 The optimum density contour plot

As can be seen from the Figure 50 and Figure 51, the maximum displacement is reduced from 0.547mm in the initial baseline design to 0.154mm. And Figure 52 and Figure 53 show that the maximum von-Mises stress decreases from 21.26MPa to 18.61MPa. Moreover, the mass, compliance of the baseline design are 19.2410E-02 Ton and 4.014461E+02mm/N respectively, while those of the optimum design are 5.77241E-02 Ton and 1.232977E+02mm/N respectively.

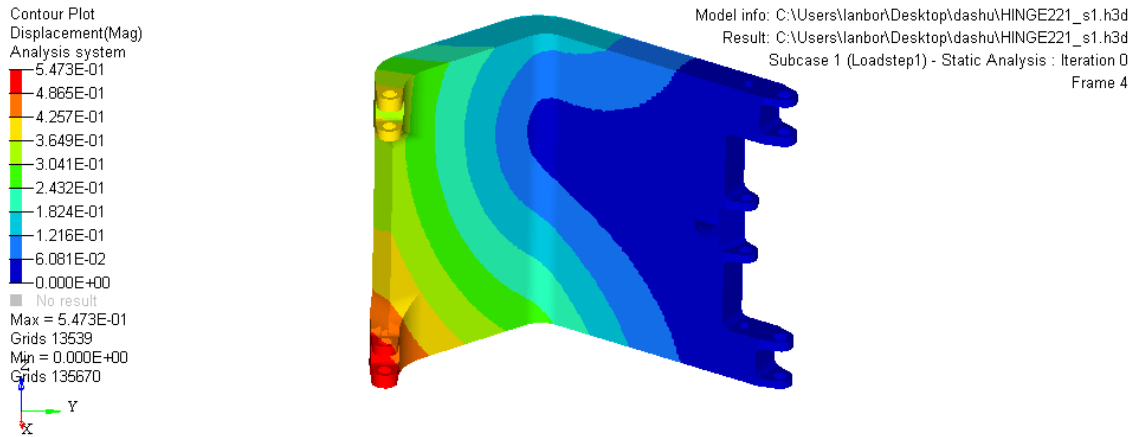


Figure 50 The baseline design displacement (mm) contour plot

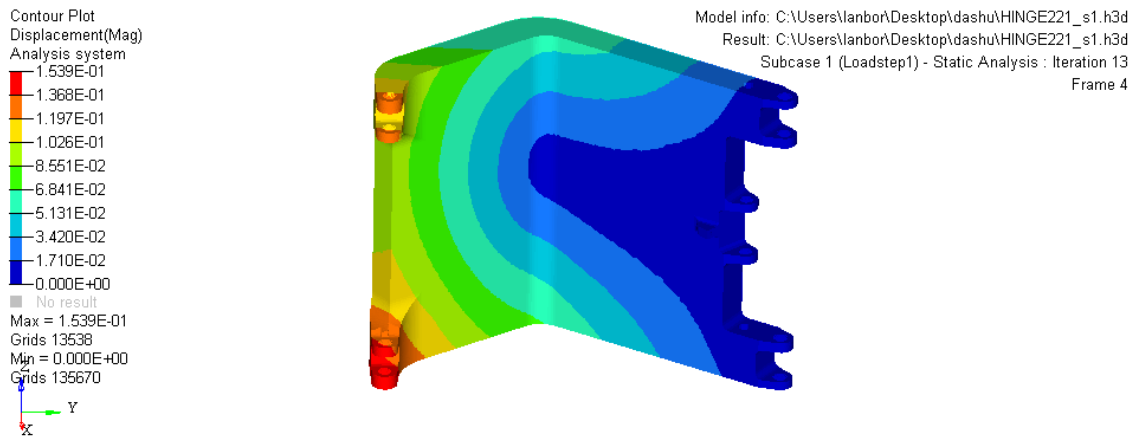


Figure 51 The optimun design displacement (mm) contour plot

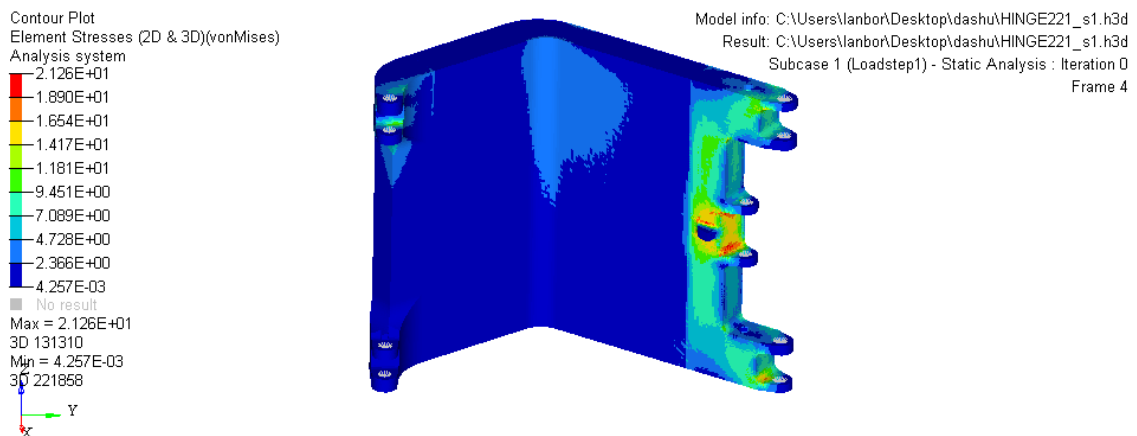
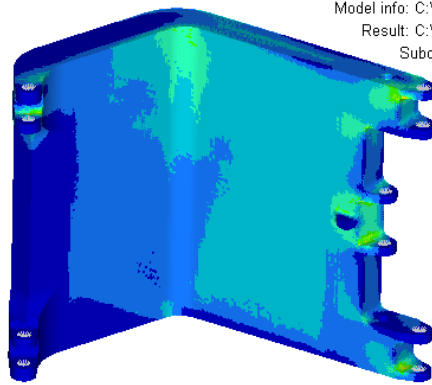
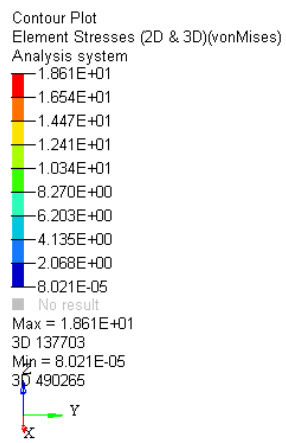


Figure 52 The baseline design von-Mises stress (MPa)



Model info: C:\Users\lanbo\Desktop\dashu\HINGE221_s1.h3d
Result: C:\Users\lanbo\Desktop\dashu\HINGE221_s1.h3d
Subcase 1 (Loadstep1) - Static Analysis : Iteration 13
Frame 4

Figure 53 The optimum design von-Mises stress (MPa)

6.2.4 Discussion

This case study demonstrates how to use the framework to solve a single objective topology optimisation problem.

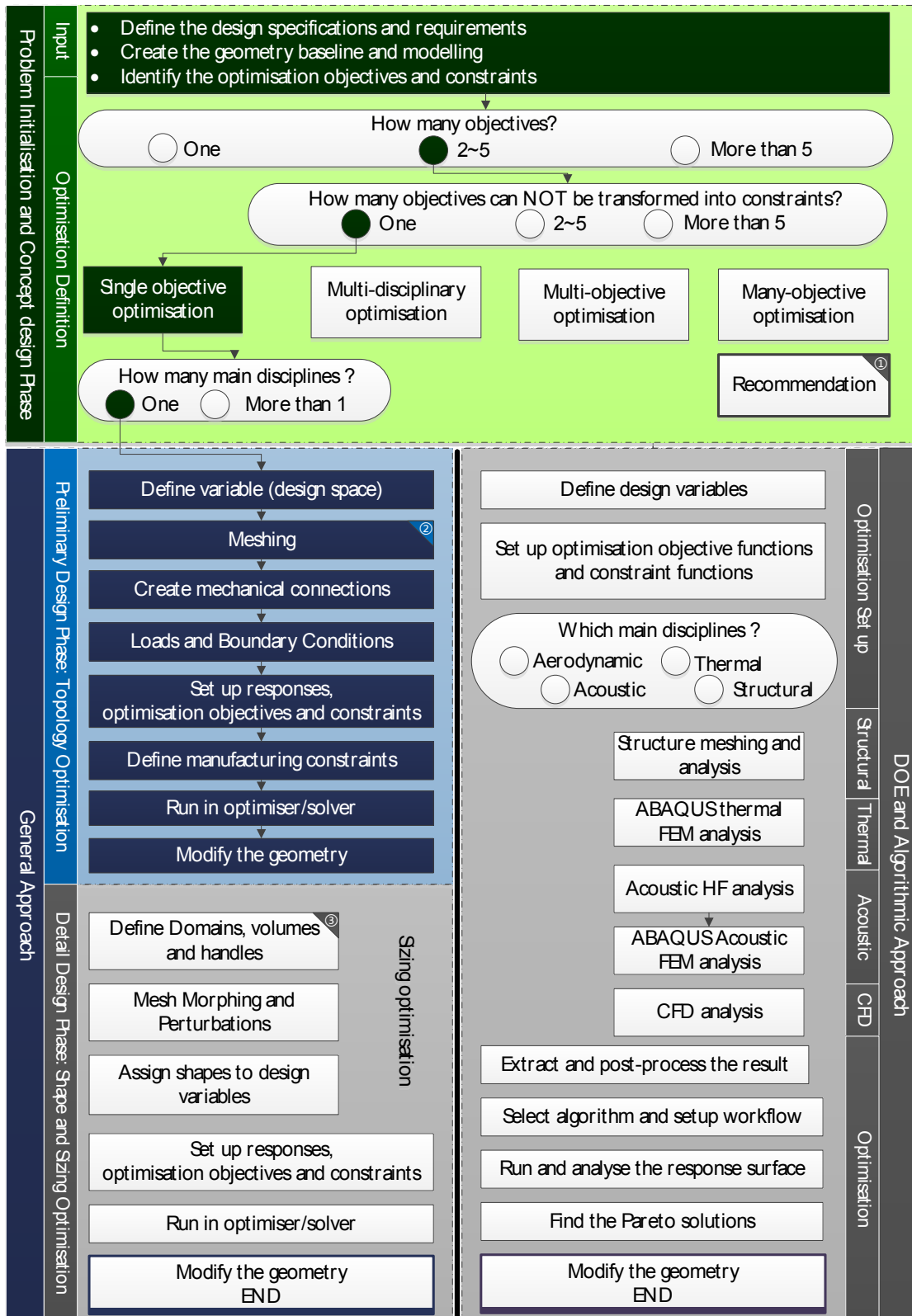
As can be seen from the result, the objective is achieved by reducing 69.3% compliance, while the constraint is strictly satisfied. The maximum displacement is reduced by 71.8% and the maximum von-Mises stress drops by 12.5%. In addition, the stress distribution of the optimum is more uniform than that of the baseline design.

It is noticed that the optimum is a cavity structure, and concerns were addressed over the possibility of manufacturing. However, the feedback from an expert in COMAC shows that this kind of cavity structure is applied in a door hinge which is designed by AIRBUS. It is also confirmed that this cavity structure has a high requirement of manufacturing ability. Hence, more manufacturing constraints should be considered if lower manufacturing abilities are available.

On the other hand, even if an enormous improvement takes place, it does not necessarily mean the result is a global optimum. The solver OPTISTRUCT automatically applies its own logic to select an algorithm, and usually achieve convergence very fast by compromising the discovery of a global optimum. In aircraft structural optimisation, since there are so many parts and components to optimise, it is very common to improve a design, rather than find the global optimum.

In this case study, some errors were encountered during the meshing process. This was due to the unsatisfactory mesh quality. Potentially this can be a common problem for most of the inexperienced engineers. Considering the importance of the FEA in aircraft structural optimisation, recommendations on meshing are given in chapter 7.

Figure 54 shows the procedure that adopted in this case study. The framework is validated and proved to be applicable to conduct a single objective topology optimisation.



① refers to recommendation 7.3.1; ② refers to recommendation 7.3.2; ③ refers to recommendation 7.3.3.

Figure 54 Case study I optimisation flow chart

6.3 Case Study II

6.3.1 Problem Definition

As described in the introduction, the second case study is defined to be a multi-objectives shape optimisation application. This case study optimises a crank which is provided by ALTAIR ENGINEERING COMPANY (UK).

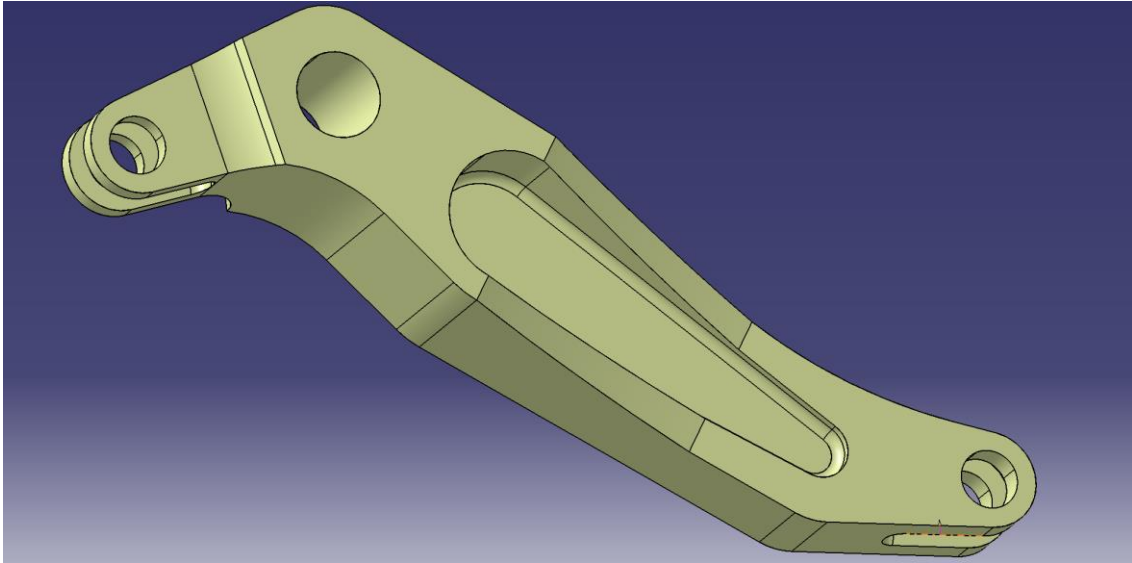


Figure 55 The crank baseline design

There are two objectives in this case study. The first one is to minimise the mass or volume, and the second one is to minimise the stress.

The optimisation constraint is set to be the displacement measured at the force application, and the value should be less than 1 mm. The boundary and loading conditions are defined and given by Altair UK. There are initially 9 design variables, of which six are length parameters and three are radius parameters.

6.3.2 Analysis and optimisation

As long as the objectives are defined, the approach can be determined to optimise this crank. Following instructions in the framework developed in chapter 6, DOE and algorithmic approach is employed to solve this multi-objective shape optimisation problem.

The mesh is generated based on the concept design model. When meshing is done, the material STEEL is created and the property is assigned to the component. The loads and boundary conditions are added to the model to apply the load conditions that the crank is subjected to. The loads are given in Table 7.

Table 7 Load distribution in the case study II

	X	Y	Z
Load Point	0	90000N	90000N

Then the shape variables are defined with HYPERMORPH.

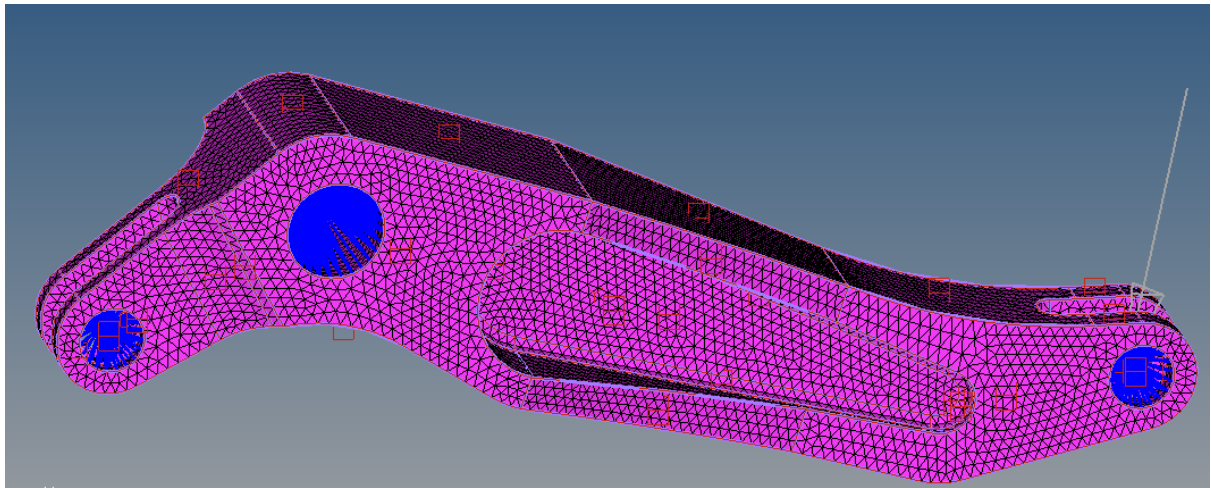


Figure 56 Meshing and FEA setup

Three responses are created: STRS, DISPL and VOL to obtain the value of the maximum stress, the displacement of a specific point and the volume of this crank. The optimisation objectives are defined with the response VOL and STRS respectively, while the optimisation constraint is generated with the response DISPL. The solver information is also added to tell the solver OPTISTRUCT what kind of analysis is being run, which results to export, etc.

Since there are initially 9 design variables, it is recommended to narrow down this number to shorten the computing time. More design variables may produce a more accurate outcome, but meanwhile it will result in a longer design phase and make the optimisation more expensive. Therefore it is very important to

decide an appropriate amount of design variables to carry out the optimisation. This can be achieved by performing a nominal run, which shows the relationship between the design response and every single design variable. This nominal run employs Latin Hypercube technique to create the DOE sequence (12 runs). Based on the outcome of the nominal run (as illustrated in figures 48 ~ 50), it is confirmed that the radius parameters are not key factors on the responses. Hence only the length variables are considered in the rest optimisation process.

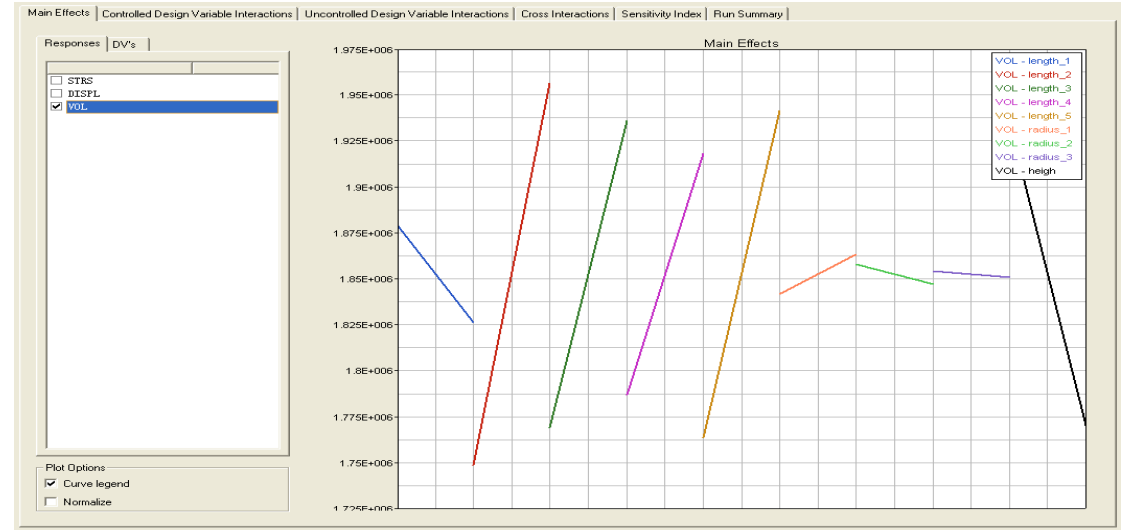


Figure 57 Design Variables Effects on Volume

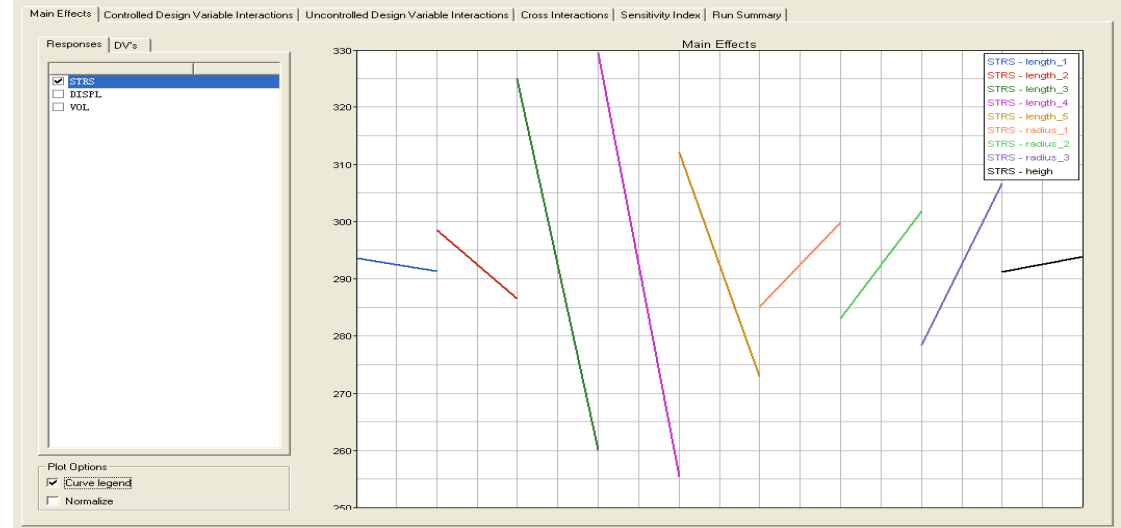


Figure 58 Design Variables Effects on Maximum stress

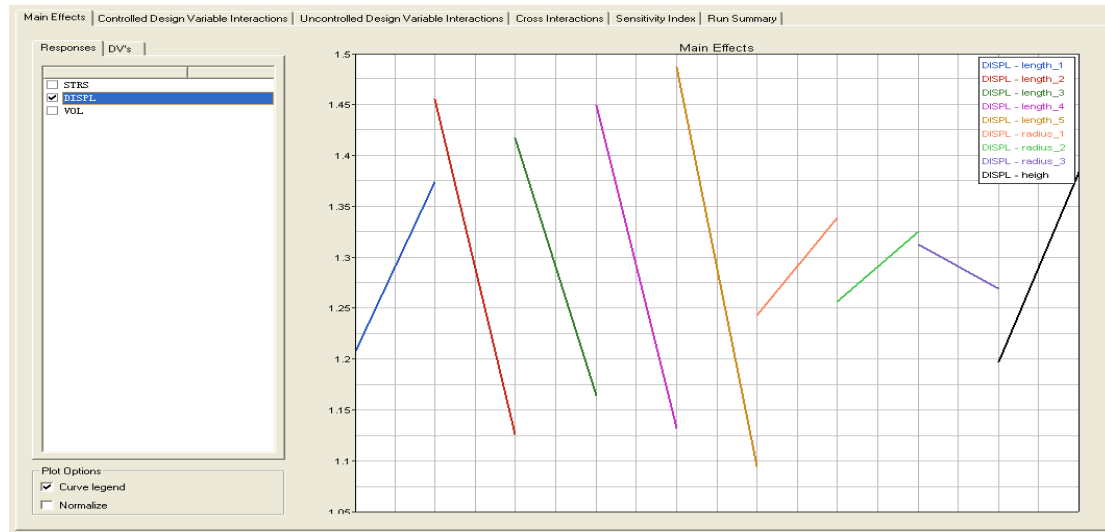


Figure 59 Design Variables Effects on Maximum Displacement

Then the design variables are narrowed and reset. Another 100 runs of the input matrix is generated with the Latin Hypercube technique. Based on those results, the response surface can be created, which is a mathematics function to simulate the solver. This will boost the calculation speed and shorten the computing time. It can be found from figures 60~61 that the design variables length_3 and length_4 have more significant effects on the responses. Therefore the length_3 and length_4 are selected to demonstrate the response surface, which is illustrated in figures 62~63. These figures show that the response surface is continuous with ups and downs. Then the response surface is examined and verified by 20 runs of validation matrix which is also created adopting the Latin Hypercube technique. The technique this optimisation employs is the Non-dominated Sorting Genetic Algorithm II (NSGA-II).

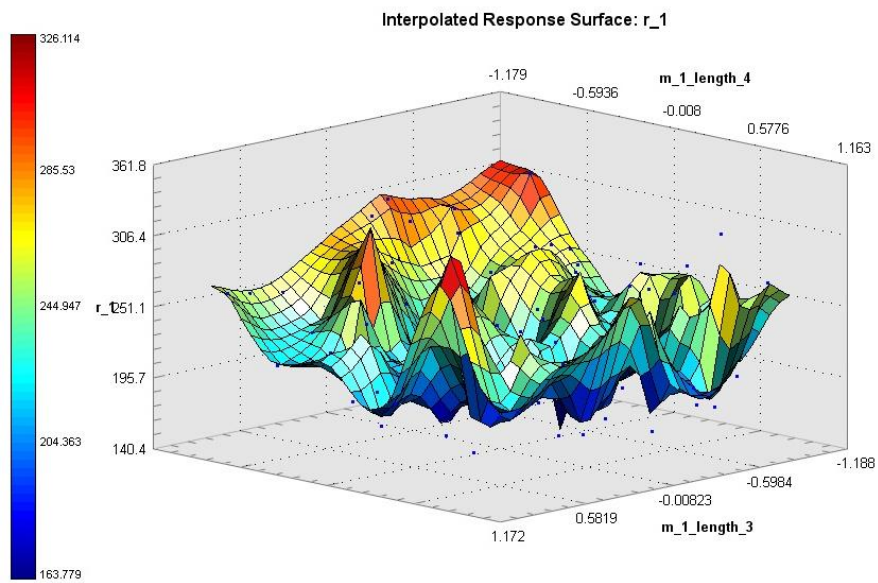


Figure 64 Response Surface of Maximum Stress (MPa)

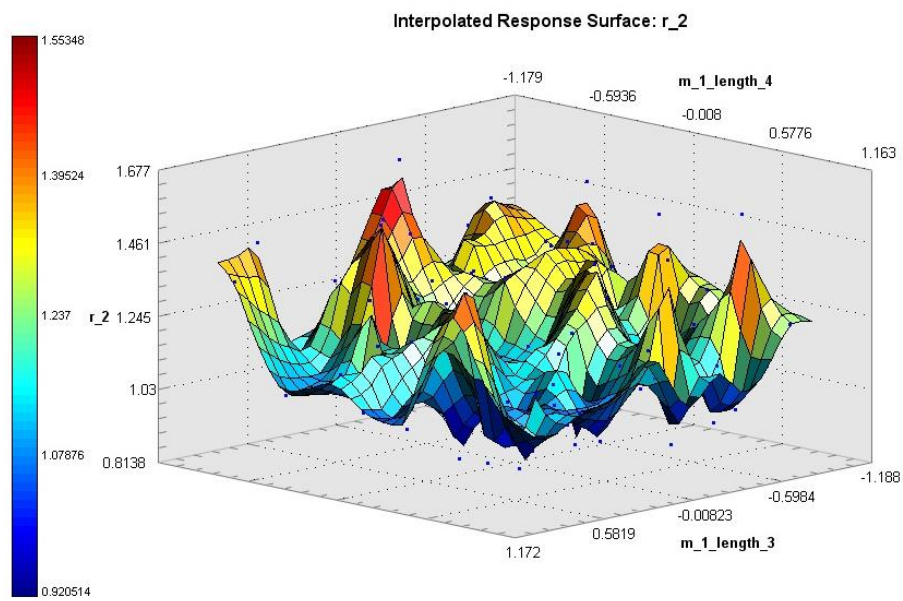


Figure 65 Response Surface of Maximum Displacement (mm)

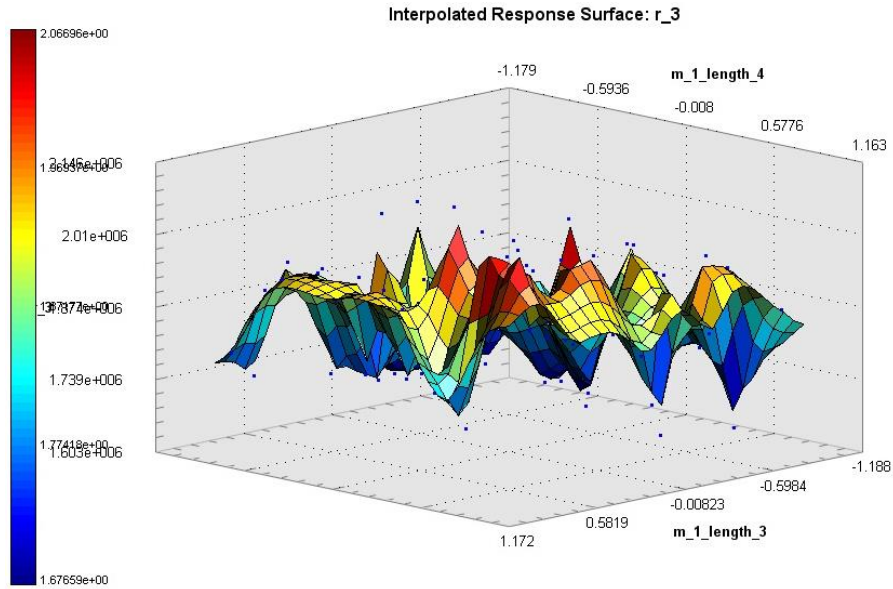


Figure 66 Response Surface of Volume (mm³)

6.3.3 Results and comparison

Figure 67 demonstrates the Pareto front obtained from the post-processor HYPERVIEW.

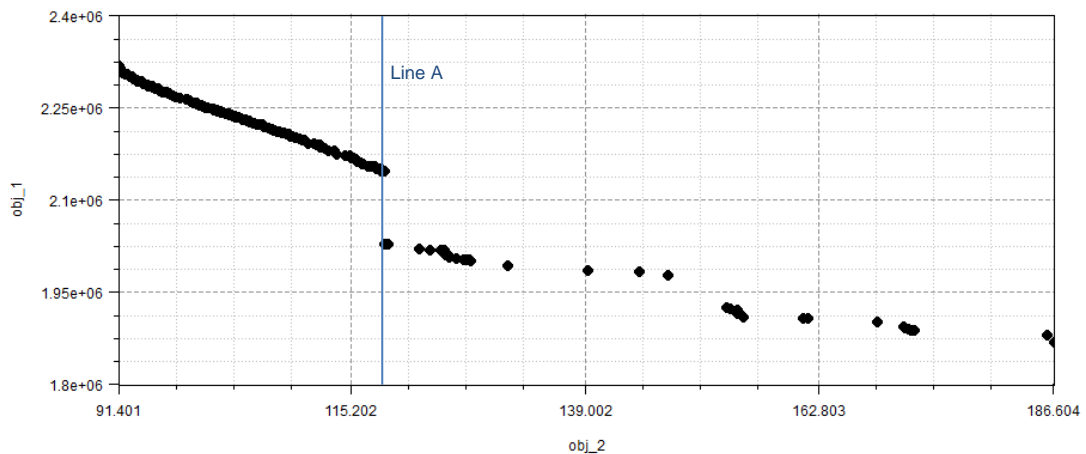


Figure 67 Pareto front(Vertical Axis:Volume, Horizontal Axis: Max_stress)

The Pareto front contains a set of optimum results, which are of the same importance considering the two objectives (minimum volume and minimum stress). They are all potential solutions, and Figure 68 shows one of them.

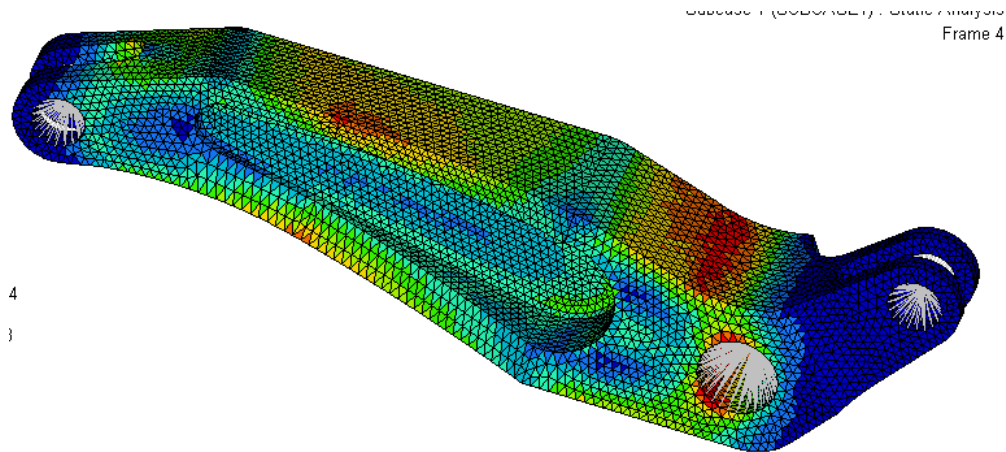


Figure 68 One solution of the optimisation

As can be seen from the Figure 69, the maximum displacement is reduced from 1.411mm in the initial baseline design to 1.120mm. And Figure 70 shows that the maximum von-Mises stress decreases from 195.3mm to 166.6mm.

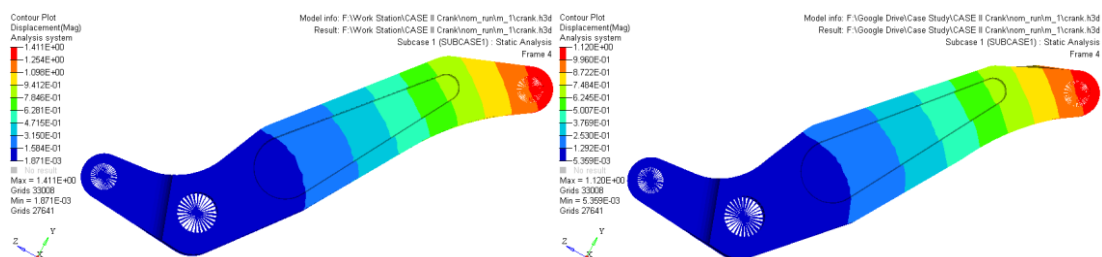


Figure 69 The comparison of displacement (mm) performance

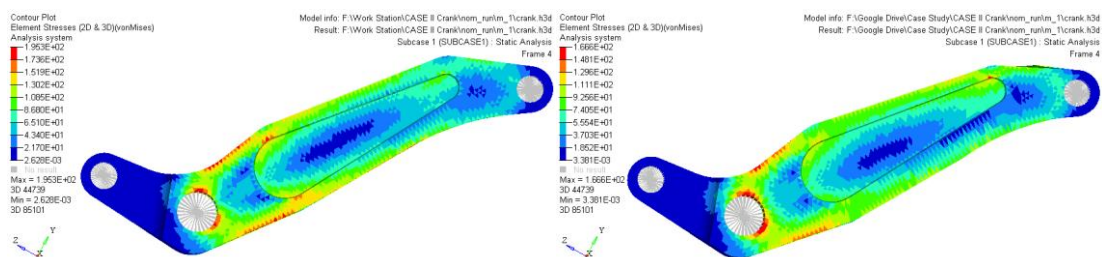


Figure 70 The comparison of stress (MPa) performance

6.3.4 Discussion

This case study demonstrates how to use the framework to solve a multi-objectives shape optimisation problem.

As can be seen from the result, the maximum displacement is reduced by 20.6%, and the maximum von-Mises stress drops by 14.6%. However, it is noticed that the volume rises slightly from $1.76676\text{E}+06 \text{ mm}^3$ to $1.90979\text{E}+06 \text{ mm}^3$ (which is 7% bigger). This is because the volume is one of the objectives. In a multi-objectives optimisation, one objective is allowed to behave less satisfactorily to achieve a better performance of another objective. Since the stress reduction is significant, it is acceptable to reasonably compromise the weight.

It is also noticed in Figure 67 that there is a sudden drop around Line A, where the volume decreases dramatically. Two designs (ID-3744 and ID-2191) near Line A are chosen and reviewed, as illustrated in Table 8 and Figure 71. ID-2191 performs slightly better than ID-3744 in stress. However when it comes to volume, ID-3744 shows its advantage. Although both designs are regarded as the optimums, the ID-3744 solution is more likely to be selected in aerospace industry.

Table 8 Performance of two solutions near Line A

ID	Maximum Stress(MPa)	Volume(mm ³)
ID-3744	120.147	2043775.7
ID-2191	119.341	2133676.3

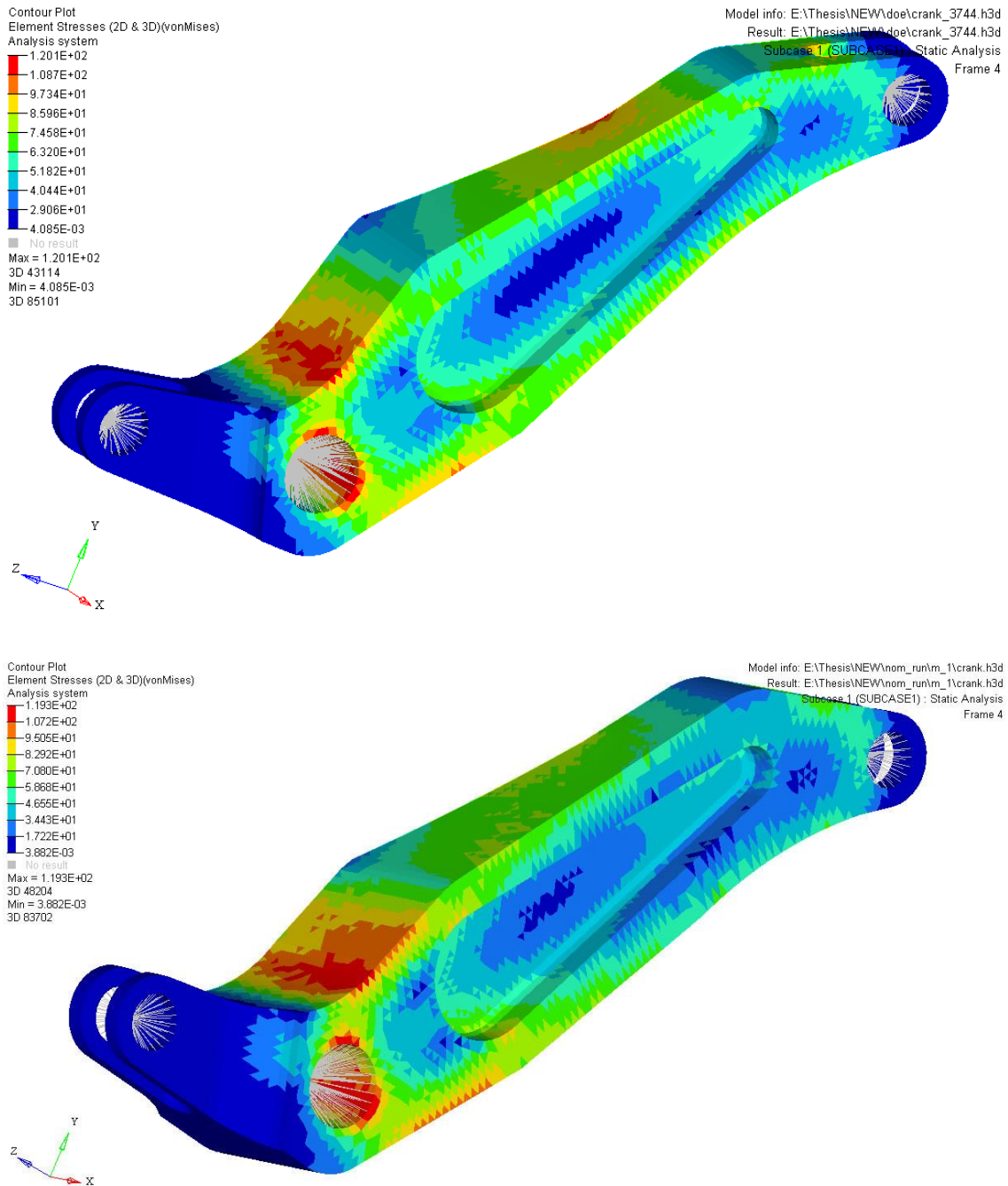
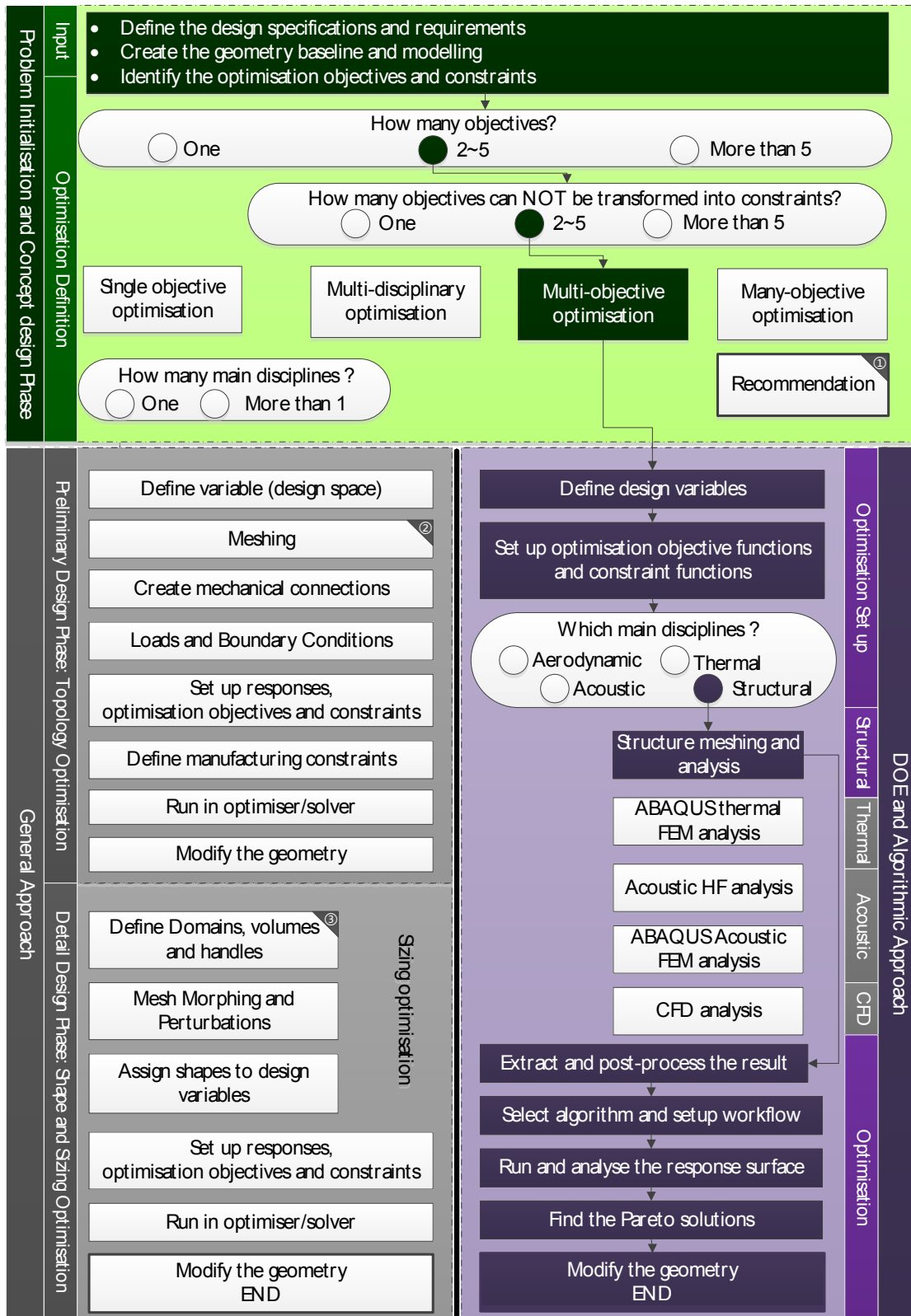


Figure 71 Comparison of two solutions near Line A (Upper ID-3744; Lower ID-2191, Unit: MPa)

The drop near Line A is because when the design variables are changed to reduce the volume, the influence upon the stress performance is relatively very low. Therefore the point close to the bottom of this line is the best solution

(minimum volume and minimum stress) and can be presented in the Pareto front, while the rest points around this line are ruled out. However, it is unknown why the volume reduction has low influence on the stress performance around this range. This will be investigated in future work.

In this case study, the framework is successfully used as a guideline to carry out the multi-objectives shape optimisation. The procedure is illustrated in Figure 72.



① refers to recommendation 7.3.1; ② refers to recommendation 7.3.2; ③ refers to recommendation 7.3.3.

Figure 72 Case study II optimisation flow chart

6.4 Case Study III

6.4.1 Problem Definition

As described in the introduction, the third case study will be a combined optimisation application, which contains two design phases and involves topology, sizing and shape optimisation approaches. A torsion link in the landing gear from COMAC is selected and optimised in this case.

The landing gear component is a very complicated system, and it is used to support the aircraft and absorb the shock and impact when it lands and taxis on the ground.



Figure 73 The landing gear, from:

<http://www.flickr.com/photos/leomoon74photography/5893783020/>

The torsion links are linked with each other to connect the two cylinders of the shock absorb bar. Those torsion links can avoid the torsion of the shock absorb bar. Meanwhile they can control the motion displacement of the cylinders when the landing gear is in operation. The torsion link can be found in Figure 74.

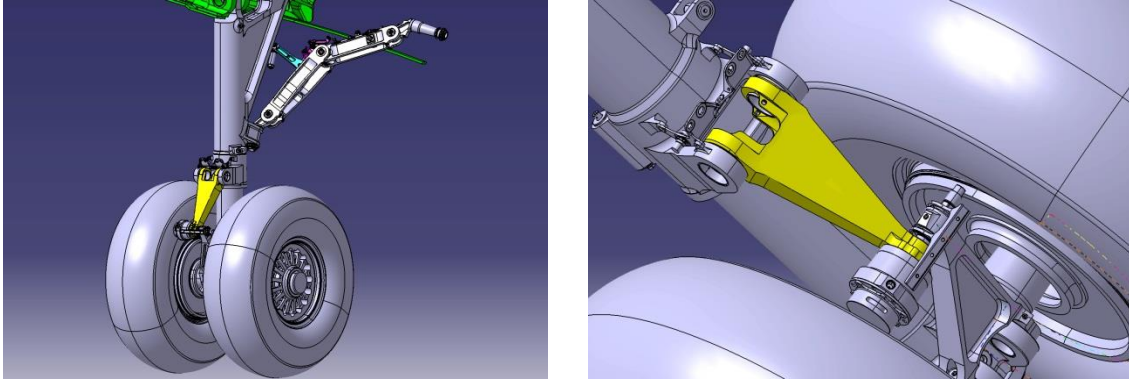


Figure 74 The position of the torsion link

In this case study, COMAC provides the loads, boundary conditions and the initial design space in the form of CATIA model (as shown in Figure 75). Since the original data and geometry model is strictly commercial and confidential, COMAC modified the input data so that it could be published. However, it does not affect the accuracy of this case study and the validation of framework generated in this study.

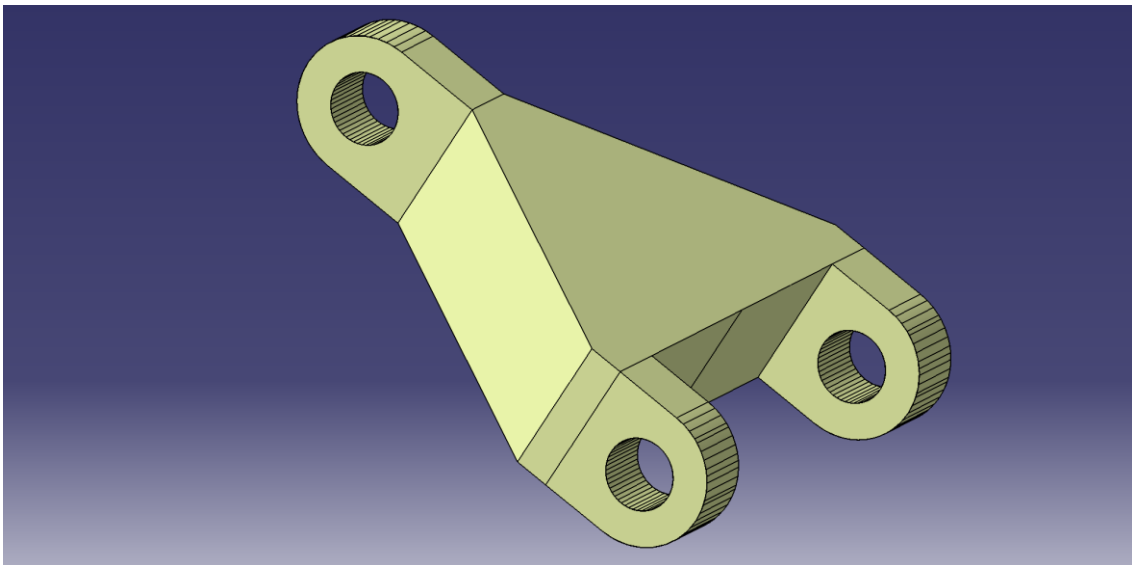


Figure 75 The baseline design of the torsion link

The objective of this optimisation is to minimise the compliance. Since there are two phases to solve this single objective mixed (topology, sizing and shape optimisation) problem, different constraints will be applied.

6.4.2 Analysis and optimisation

According to the framework, it is recommended to adopt the general approach to optimise this torsion link. The topology technique is conducted in the concept phases to obtain the optimised material distribution. Then sizing or/and shape optimisation is carried out to get the final result in the detail design phase.

The design space geometry obtained from COMAC is imported into HYPERMESH. Once the geometry is cleaned up, the solid is created based on the surface imported from the baseline CATIA IGES file. Then the mesh is generated with its quality checked.

When meshing is finished, the material STEEL is created and properties are assigned to the design component and non-design component respectively.

Then the loads and boundary conditions are added to the model to apply the load conditions that the torsion link is subjected to.

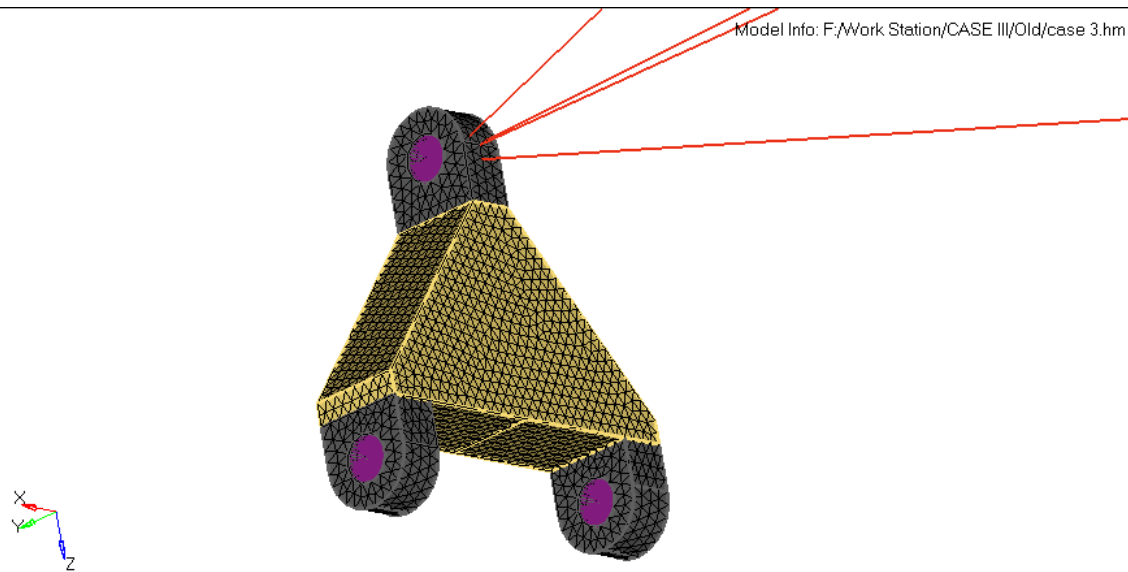


Figure 76 Pre-processing of the torsion link model

Various responses are created to generate the objective (function) or the constraint (function). In this case, the responses VOLUMEFRAC and COMPL are generated, representing the volume fraction and compliance respectively. The optimisation objective OBJECT is defined, based on the response COMPL, to minimise the compliance. Meanwhile, the optimisation constraint CONSTR is

created with the response VOLUMEFRAC, ensuring the final optimum is at least 70% lighter than the initial baseline design. For this hinge arm, the manufacturing constraint is the draw direction requirement.

Then the data is submitted to the processor, which is OPTISTRUCT in this case. The result of this run is illustrated in Figure 77.

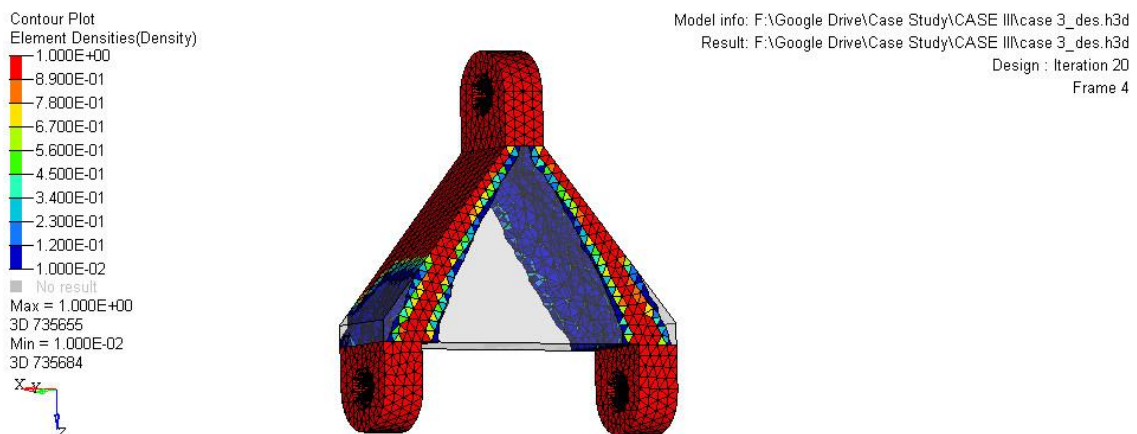


Figure 77 The result of the topology optimisation

The FEA result can be exported to an IGS file with OSSMOOTH tool, and be modified by CATIA. Then the geometry of the concept design is generated, as shown in Figure 78.

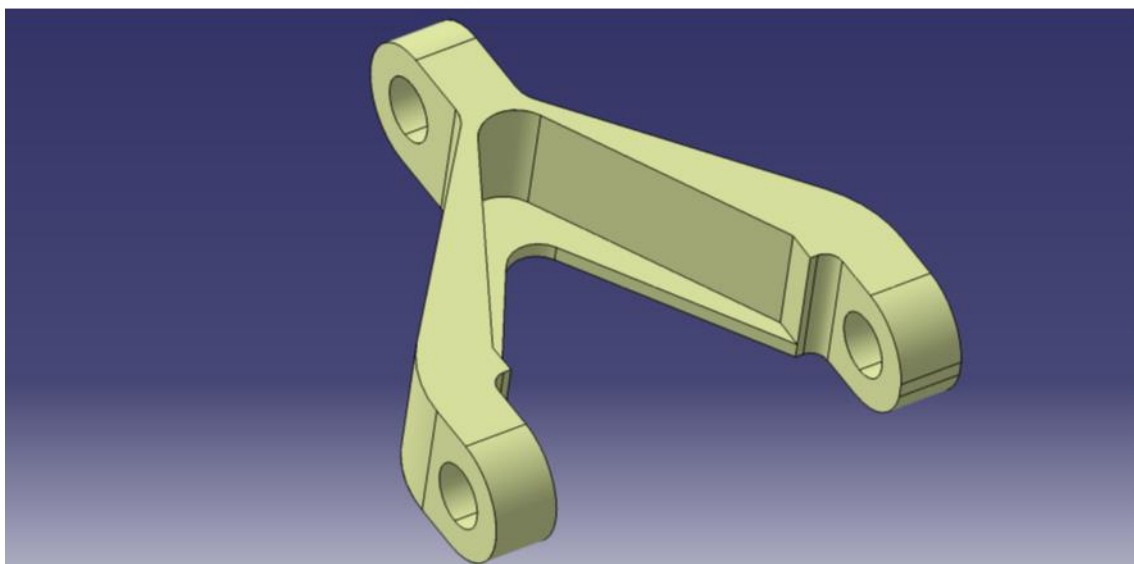


Figure 78 The outcome of the concept design

Before entering the next stage, it is crucial to analyse the new torsion link model, and concentrate on the potential optimisation areas to save the computation time. The Figure 79 shows that the maximum displacement is less than 0.29mm, which is acceptable. In addition, the Figure 80 illustrates the Von-Mises stress distribution, and indicates the maximum value is 57.2MPa. The stress distribution is not uniform and the zones of high stress value (marked in red) are highlighted portions to optimise.

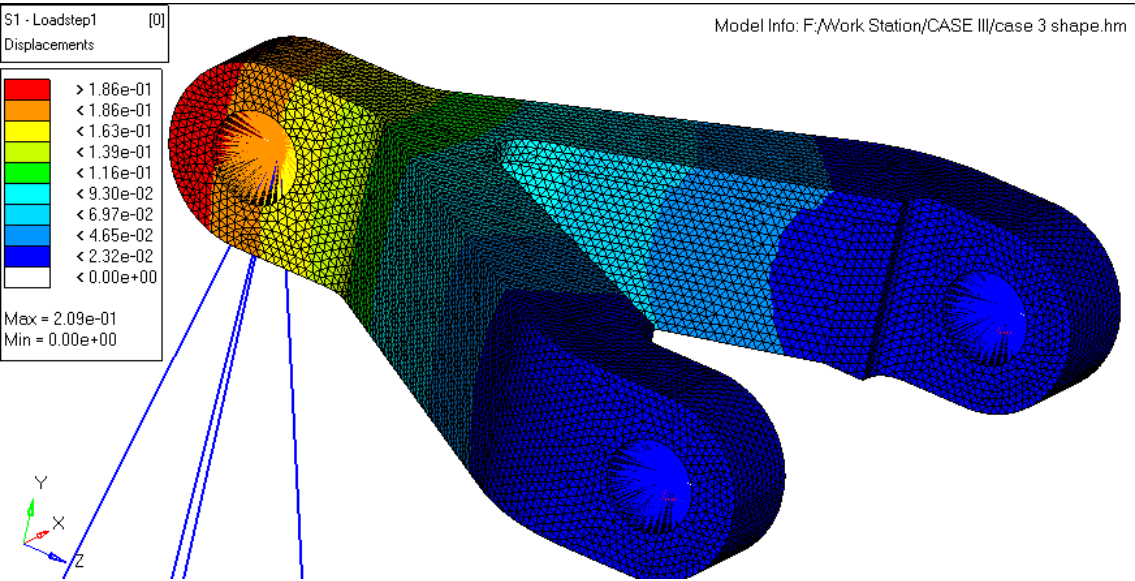


Figure 79 Displacement (mm) analysis of the updated torsion link

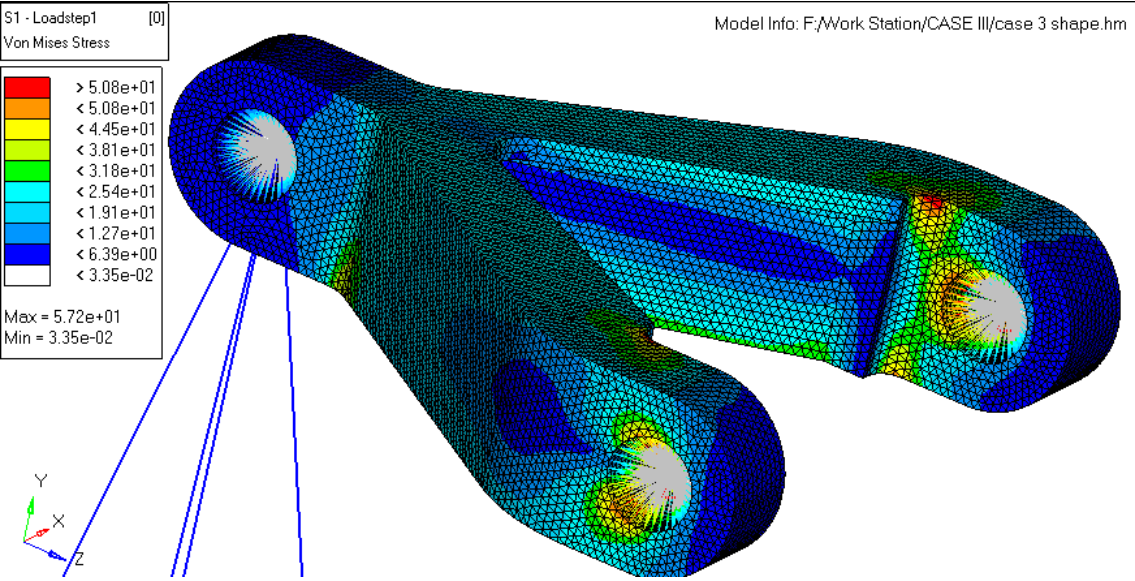


Figure 80 Stress (MPa) analysis of the updated torsion link

To start the detail design phase, the domains, volumes and handles should be defined so the deformation can be controlled by the solver OPTISTRUCT. Mesh morphing and perturbations are also carried out to set up the shape parameters. Then the shapes parameters are assigned to design variables. In this case study, the Free Shape Function is adopted to define the shape variables, which is marked in white in Figure 81.

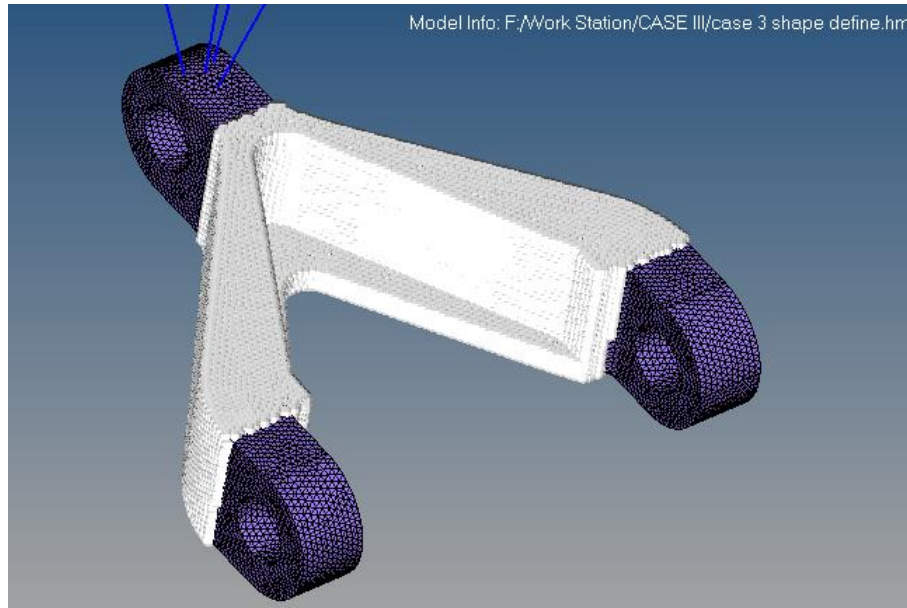


Figure 81 design variables

In this run, the response is the maximum stress of the highlighted zones obtained from the previous step. This response is relevant to the optimisation objective, which is to minimise the maximum stress of the highlighted zones.

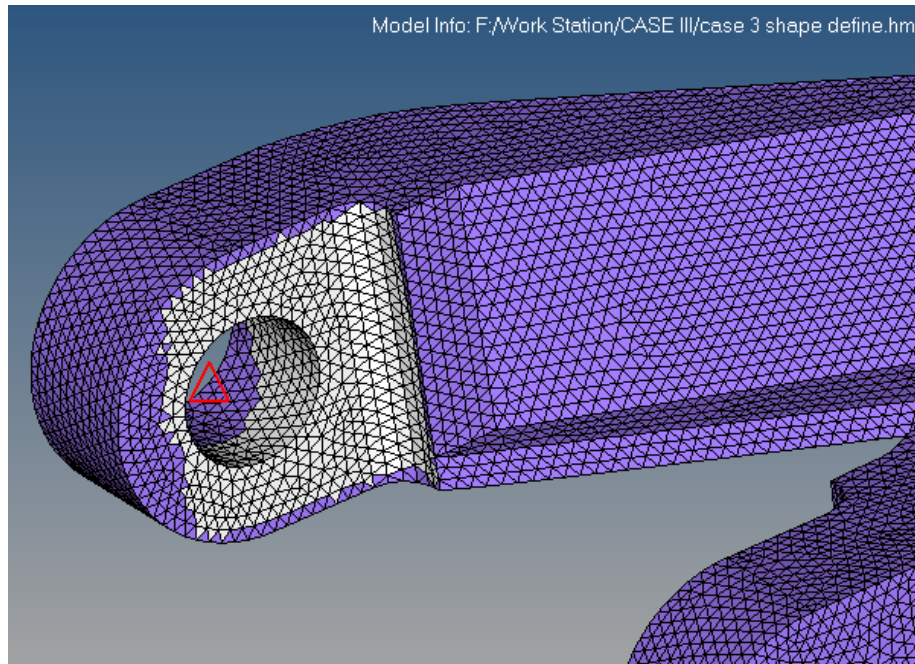


Figure 82 the highlighted zone

6.4.3 Results and comparison

When the solver OPTISTRUCT completes the task, the result can be read and visualised with HYPERMESH. The Figure 83 demonstrates the portions which are modified and optimised.

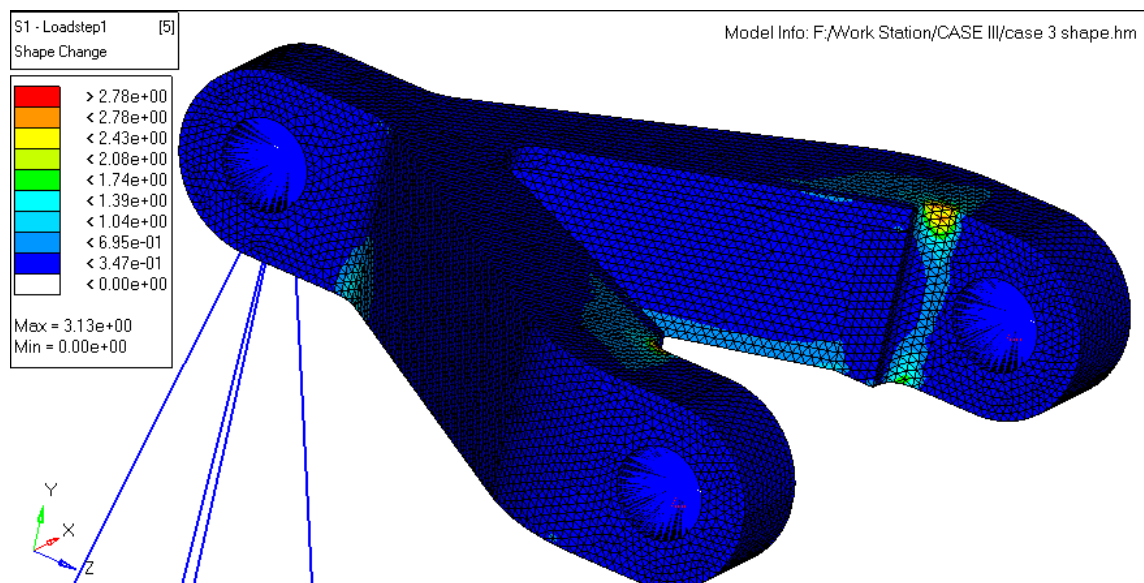


Figure 83 The shape change (mm) distribution

As can be seen from Figure 84 and Figure 85, the maximum displacement is reduced from 1.13mm to 0.2mm(82.3% less), and the maximum stress decreases from 227.3MPa to 55.7MPa(75.5% less).

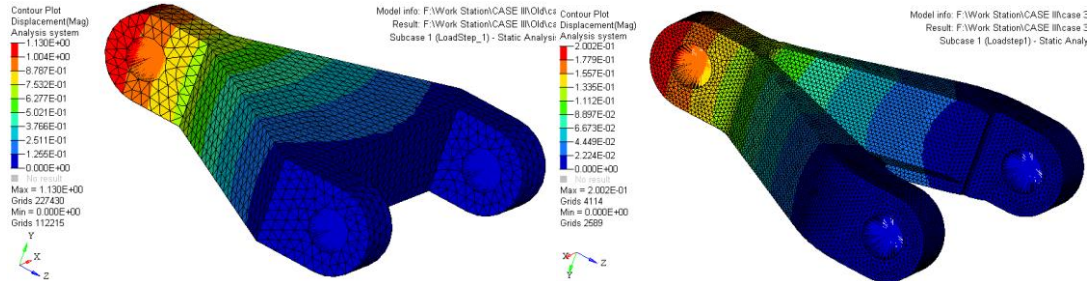


Figure 84 The comparison of displacement (mm) performance

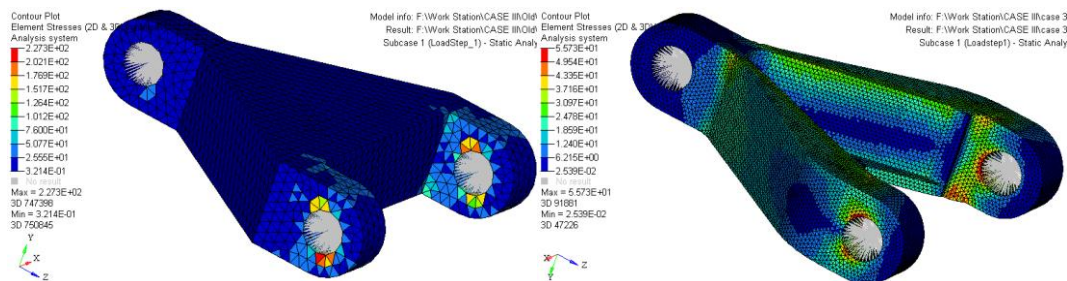


Figure 85 The comparison of stress (MPa) performance

6.4.4 Discussion

This case study demonstrates how to use the framework to solve a combined optimisation problem.

In this case study, there are two stages to conduct the optimisation. The improvement of each phase is shown in Table 9. It is learnt that the reduction of volume (or weight) is achieved mainly through the preliminary design, in which the topology optimisation is employed. As a matter of fact, the volume (or weight) can even increase in the detail design phase. This happens in this case study. The volume grows by 1.3% to fulfil the improvement of the compliance performance, which is up to 65% reduction.

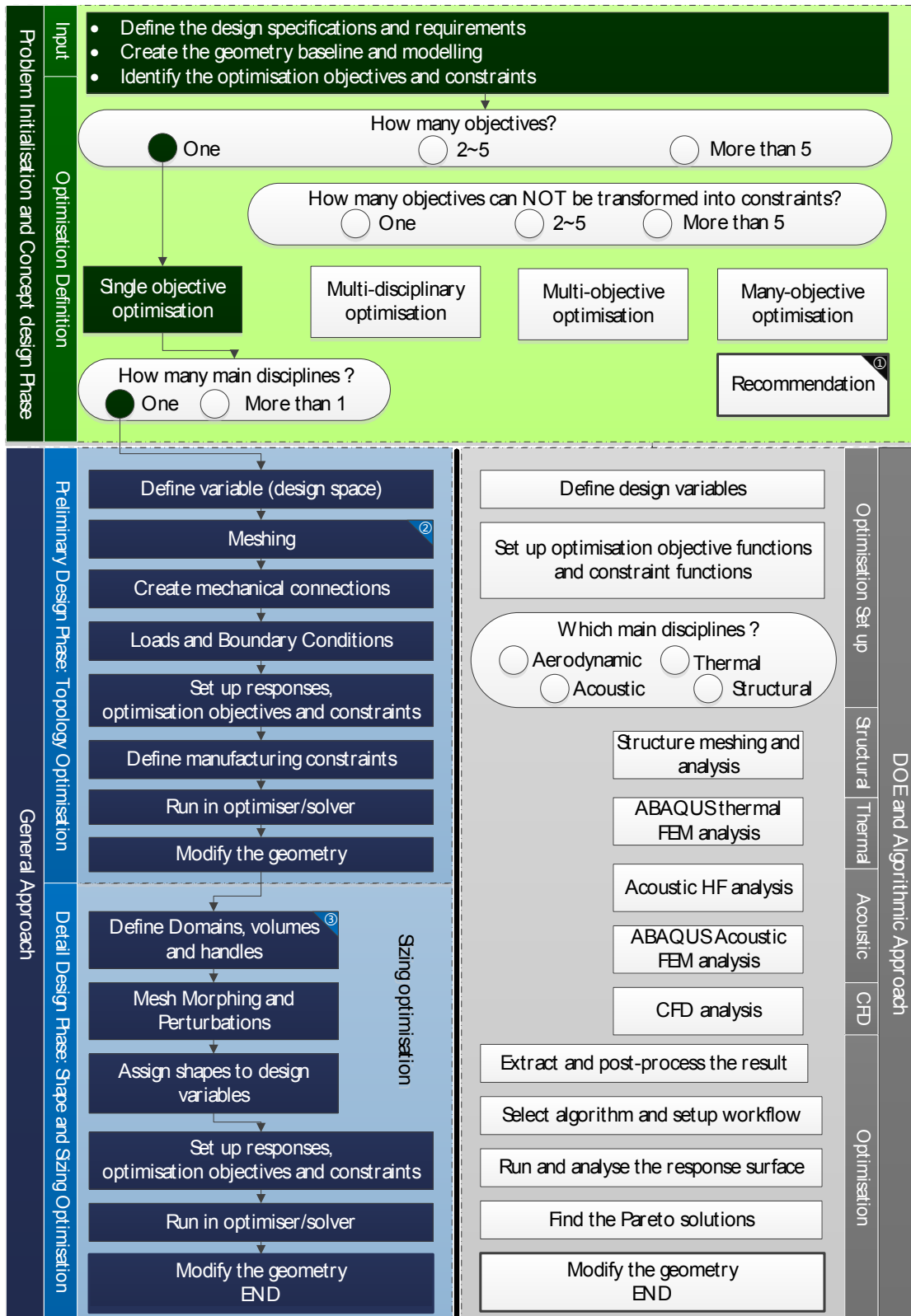
Table 9 The improvement of each phase

Parameter	Concept design	Preliminary design	Detail design	Ratio*	Ratio**
Volume (mm ³)	5.45383E+06	1.63615E+06	1.65744E+06	+1.30%	-69.6%
Stress (MPa)	2.27300E+02	5.72000E+01	5.57300E+01	-2.56%	-75.4%
Compliance (mm/N)	4.69404E+03	2.32313E+03	8.12320E+02	-65.0%	-82.7%

* indicates the ratio between the final improvement and the preliminary design.

** indicate the ratio between the final improvement and the concept design.

The framework is successfully used as a guideline to carry out the mixed optimisation. The workflow of this case study is illustrated in Figure 86.



① refers to recommendation 7.3.1; ② refers to recommendation 7.3.2; ③ refers to recommendation 7.3.3.

Figure 86 Case study III optimisation flow chart

6.5 Summary

In this chapter, case studies are carried out to demonstrate how the framework works. There are three case studies in this paper, and all of them are from industries. The first one is a door hinge with single-objective topology optimisation problem. The second one is a crank with multi-objective shape optimisation problem. And the third one is a landing gear torsion link with a combined (topology, shape and sizing) optimisation problem. The general approach is conducted for the first and third case study, while the DOE and algorithmic approach is adopted to solve the subsequent case study problem.

The framework is applied in those case studies, and the satisfactory result proves that this framework is practical and useful. Constructive feedback and comments are given by experts from COMAC and ALTAIR ENGINEERING UK, which improves the accuracy of these case studies.

7 DISCUSSION AND RECOMMENDATIONS

7.1 Introduction

The optimisation technique is developing very fast, and because of its importance, many methods and approaches have been found and published. However, it will take an engineer a long time to learn and master those design and optimisation techniques. Hence, this thesis gives some recommendations on aircraft design optimisation.

7.2 When to use optimisation

There are some general guidelines for how to determine if optimisation should be employed:

- a) For a brand new product which has no existing constraints, concept design optimisation methods is adopted to define the design space, and deliver novel and unpredicted outcome that result in enhanced performance. It can also reduce design time by producing better initial concepts that require minimum modification later in the design cycle.
- b) When the reduced weight or other objective has met the optimisation requirement through the application of a single optimisation method, such as the topology optimisation in the preliminary design phase, considering the cost and time needed to do optimisation for the detail design phase, it can be advised to give up further optimisation, if a relatively minor amount of extra weight could be reduced. But for aircraft structures, because there is high value in removing weight from existing parts, the optimisation for the detail design phase usually provides significant value.
- c) If a product is experiencing failures during operation, detail design optimisation can improve the design to reduce stresses while considering the entire product. Therefore a fix made to take care of one problem will not create a separate unintended problem.

7.3 How to do optimisation

7.3.1 Problem Initialisation

In the phase of Design and Optimisation Problem Initialisation, the number of objectives is a vital factor to decide what type of problem it will be and which approach will be adopted. Hence the objective should be defined carefully. Considering the time limit and research cost, it is advised to convert the objectives to constraints as many as possible, and only take the most important discipline into account. Although it will risk the possibility to find the best solution, the result is still acceptable since to some extent the improvement is achieved. And this is commonly adopted in the aerospace industry to optimise most airframe parts. Nevertheless, when it comes to the component overall configuration optimisation, it is better to keep more than one objective, and consider reasonable disciplines.

Usually the amount of objectives can be limited to 1 to 5. However in some case there may be 5 or even more objectives, which are defined as many-objective optimisation. It is out of the scope of this study.

7.3.2 Meshing

Meshing is critical to the finite element analysis as the quality of the mesh has a great influence on the accuracy of the results obtained. Therefore the mesh quality needs to be checked. A neat mesh of high quality can produce satisfactory result, while a defective grid, with the mesh deformation beyond a certain range, can significantly decrease the accuracy. That is the reason why in this case the tetra mesh is created based on the shell mesh.

7.3.3 Shape variables

For the shape optimisation, the design variables need to be defined with domains, volumes and handles by morphing. However, in some optimisation tools this can be done automatically. The Free Shape Optimisation Function in HYPERWORKS is such kind of tool that can roughly create the shape variables.

7.4 Summary

This chapter presents the discussion and recommendation of how to manage the optimisation in aircraft structural design, including when to carry out the optimisation and how to make it.

Useful and practical suggestions are also highlighted in this chapter for inexperienced engineers and designers. Those recommendations are connected with the framework, making them clearly accessible.

8 CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

From this study, the following conclusions can be drawn:

- a) The built-in optimisation modules in the CAD/FEA tools may boost the efficiency, but may contain few algorithms, and take long time to find the optimum.
- b) The optimisation is not always applicable in every phase of the design.
- c) The preliminary phase is crucial for the whole optimisation. The detail design could be skipped if the objective is weight reduction.
- d) The topology optimisation can result in the best distribution of material, but may rise to a challenge of the manufacturing abilities. For countries such as China, since their manufacturing abilities are still developing, more manufacturing constraints should be considered.
- e) Although the DOE and algorithmic approach is not widely used in the aerospace industry at present, it is becoming popular for the researcher to adopt it to conduct optimisation. The widely adopted optimisation approach in aerospace engineering practise significantly improves the performance of structures; however the solution may not be the real optimum. Engineers are recommended to learn the DOE and algorithmic approach and try to find the real optimum. The framework developed in this study could be a good guideline.
- f) In the past, little can be found in the publications about the systematic framework for the aircraft structural design. However, with the instructions of the framework and recommendations in this study, even inexperienced engineers can easily find the approach to carry out their optimisation tasks.

8.2 Future work

In the study, the DOE and algorithmic approach is introduced. However, this approach is not widely adopted in the aircraft industry. The accuracy and computing performance of the algorithm still need to improve. If the DOE and algorithmic approach can achieve a high quality result within a limited time, it could be more popular.

As introduced in the first chapter, only the airframe structures of the commercial aircraft is discussed in this study. The techniques about composite material, engine, system structures, interior structures or uncertainty problems are not involved. However, the composite material is adopted widely in aircraft structures nowadays, and its good performance has been proved by many aerospace companies. Therefore the composite structure design and optimisation will be studies in the future. In addition, the material selection plays an important role in composite structural optimisation. Hence the composite material selection will also be part of the future work.

The results obtained from the optimisation cannot update the CAD geometry parameters automatically, which needs to be converted into CAD model. Engineers have to redraw parts of the design based on the FEA geometry, particularly in the topology optimisation. Although there are existing tools such as OSSMOOTH which can export the optimum geometry into different CAD format, the outcome is not a close or constant surface. Moreover, it is usually impossible to manufacture. Therefore it is very important and essential to develop the tool to automatically and accurately deliver the optimum design to CAD models in the future.

Although numerous papers and books have been referred to, this study still has its limitation on literature review. Hence more publication will be read to update the knowledge of optimisation.

REFERENCES

- Allen, M. and Maute, K. (2005), "Reliability-based shape optimization of structures undergoing fluid-structure interaction phenomena", *Computer Methods in Applied Mechanics and Engineering*, vol. 194, no. 30-33, pp. 3472-3495.
- Altair (2009), *Concept Design with Topology and Topography Optimization*, .
- AN, W., LI, W. and GOU, Z. (2006), "Multi-objective Optimization Design of Wing Structure with the Model Management Framework", *Chinese Journal of Aeronautics*, vol. 19, no. 1, pp. 31-35.
- Arias-Montano, A., Coello Coello, C. and Mezura-Montes, E. (2012), "Multi-Objective Evolutionary Algorithms in Aeronautical and Aerospace Engineering", .
- Bäck, T., Hammel, U. and Schwefel, H. (1997), "Evolutionary Computation: Comments on the History and Current State", *IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION*, vol. 1, pp. 3-17.
- Balesdent, M., Bérend, N., Dépincé, P. and Chriette, A. (2012), "A survey of multidisciplinary design optimization methods in launch vehicle design", *Structural and Multidisciplinary Optimization*, vol. 45, no. 5, pp. 619-642.
- Bulman, S., Sienz, J. and Hinton, E. (2001), "Comparisons between algorithms for structural topology optimization using a series of benchmark studies", *Computers & Structures*, vol. 79, no. 12, pp. 1203-1218.
- Chapman, C. D. (1994), *Structural Topology Optimization Via the Genetic Algorithm*, Massachusetts Institute of Technology, Department of Mechanical Engineering.
- Chintapalli, S., Elsayed, M. S. A., Sedaghati, R. and Abdo, M. (2010), "The development of a preliminary structural design optimization method of an aircraft wing-box skin-stringer panels", *Aerospace Science and Technology*, vol. 14, no. 3, pp. 188-198.
- Christensen, Peter W., Klarbring, A. (2008), *An Introduction to Structural Optimization*, Springer Netherlands, Dordrecht.
- Chen, L., & Zhang, Y. (2013). A Study on the application of material selection optimization approach for structural-acoustic optimization. *Materials & Design*.
- Coello Coello, C. A. (2006), "Evolutionary multi-objective optimization: a historical view of the field", *Computational Intelligence Magazine, IEEE*, vol. 1, no. 1, pp. 28-36.
- Corne, D. W. and Knowles, J. D. (2007), "Techniques for highly multiobjective optimisation: some nondominated points are better than others", *Proceedings of the 9th annual conference on Genetic and evolutionary computation*, London, England, ACM, New York, NY, USA, pp. 773.
- Depince, P., Guedas, B. and Picard, J. (2007), "Multidisciplinary and multiobjective optimization: Comparison of several methods", *7th World Congress on Structural and Multidisciplinary Optimization*, 21 May - 25 May, Seoul, Korea, COEX, .

- Engelbrecht, A. P. (2007; 2007), "Appendix A: Optimization Theory", in *Computational Intelligence*, John Wiley & Sons, Ltd, , pp. 551-579.
- Ermolaeva, N. S., Castro, M. B., & Kandachar, P. V. (2004). Materials selection for an automotive structure by integrating structural optimization with environmental impact assessment. *Materials & design*, 25(8), 689-698.
- FAA,(2010), "PART 25: transport category", *Federal Aviation Regulations*, United States.
- Garc\`ia, M. J., Boulanger, P. and Henao, M. (2008), "Structural optimization of as-built parts using reverse engineering and evolution strategies", *Structural and Multidisciplinary Optimization*, vol. 35, no. 6, pp. 541-550.
- Greiner, D., Winter, G. and Emperador, J. M. (2001), "Optimising frame structures by different strategies of genetic algorithms", *Finite Elements in Analysis and Design*, vol. 37, no. 5, pp. 381-402.
- Haftka, R. T. and Grandhi, R. V. (1986), "Structural shape optimization—A survey", *Computer Methods in Applied Mechanics and Engineering*, vol. 57, no. 1, pp. 91-106.
- Hansen, L. U. and Horst, P. (2008), "Multilevel optimization in aircraft structural design evaluation", *Computers & Structures*, vol. 86, no. 1–2, pp. 104-118.
- Hsu, Y. (1994), "A review of structural shape optimization", *Computers in Industry*, vol. 25, no. 1, pp. 3-13.
- Kaufmann, M., Zenkert, D. and Wennhage, P. (2010), "Integrated cost/weight optimization of aircraft structures", *Structural and Multidisciplinary Optimization*, vol. 41, no. 2, pp. 325.
- Kaveh, A., Hassani, B., Shojaee, S. and Tavakkoli, S. M. (2008), "Structural topology optimization using ant colony methodology", *Engineering Structures*, vol. 30, no. 9, pp. 2559-2565.
- Kirsch, U. (2008), "Static Analysis", in Springer Netherlands, , pp. 1-36.
- Kirsch, U. (1993), *Structural optimization: fundamentals and applications*, Springer-Verlag.
- Laban, M. (2009), "Multidisciplinary Wing Design Optimization", *Advances in Collaborative Civil Aeronautical Multidisciplinary Design Optimization*, Vol. 233, Virginia, US, pp. 127.
- Langer, H., Pühlhofer, T., & Baier, H. (2002, September). An approach for shape and topology optimization integrating CAD parametrization and evolutionary algorithms. In 9th AIAA/ISSMO Symposium and Exhibit on Multidisciplinary Analysis and Optimization, Atlanta, GA (Vol. 4, No. 6).
- Ledermann, C., Ermanni, P. and Kelm, R. (2006), "Dynamic CAD objects for structural optimization in preliminary aircraft design", *Aerospace Science and Technology*, vol. 10, no. 7, pp. 601-610.
- Locatelli, D., Mulani, S. B. and Kapania, R. K. (2010), "Supersonic Wing Box Weight Optimization Using Curvilinear Spars and Ribs (SpaRibs)", .
- Logan, D. L. (2007). A first course in the finite element method. Cengage Learning.

- Narayan, L. (2008), *Computer Aided Design And Manufacturing*, Prentice-Hall Of India Pvt. Limited, New Delhi.
- Niu, M. C. (2006), *Airframe structural design: practical design information and data on aircraft structures*, 3rd ed, Conmilit Press, Hong Kong.
- Oduguwa, V., Roy, R. and Farrugia, D. (2007), "Development of a soft computing-based framework for engineering design optimisation with quantitative and qualitative search spaces", *Applied Soft Computing*, vol. 7, no. 1, pp. 166-188.
- Pahl, G. (2007), *Engineering Design: A Systematic Approach*, 3rd ed, Springer-Verlag, London, UK.
- Qiu L.(2013), *Material selection combined with optimal structural design for mechanical parts*, *Journal of Zhejiang University SCIENCE A VL 14IS*, Hangzhou,China.
- Quejji, Y. (2009), *Finite element modelling of wind turbine* (Master thesis), CRANFIELD UNIVERSITY, UK.
- Rangaiah, G. P. (2009), *Multi-Objective Optimization: Techniques and Applications in Chemical Engineering*, World Scientific.
- ROY, R. (1997), *Adaptive search and the preliminary design of gas turbine blade* (Ph.D. Thesis thesis), University of Plymouth, UK.
- ROY, R. and MUSSA, R. (1998), "Flexible optimisation within a CAD/CAM environment for the automotive industry", *the 31st ISATA Conference*, Vol. 98ME061, 2-5 June, Dusseldorf, Germany, ISATA, England, pp. 277-284.
- Roy, R., Hinduja, S. and Teti, R. (2008), "Recent advances in engineering design optimisation: Challenges and future trends", *CIRP Annals - Manufacturing Technology*, vol. 57, no. 2, pp. 697-715.
- Roy, R., Jared, G. and Mussa, R. (2002), "Curve and surface optimization within the CAD/CAM environment", *Journal of Engineering Design*, vol. 13, no. 2, pp. 121-139.
- Roylance, D. (2001), "Finite Element Analysis", *Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge*, .
- Saleem, W., Yuqing, F. and Yunqiao, W. (2008), "Application of Topology Optimization and Manufacturing Simulations-A new trend in design of Aircraft components", *Proceedings of the International MultiConference of Engineers and Computer Scientists*, Vol. 2, Citeseer, .
- Sakundarini, N., Taha, Z., Rashid, S. H. A., & Ghazila, R. A. R. (2013). Optimal Multi-Material Selection for Lightweight Design of Automotive Body Assembly Incorporating Recyclability. *Materials & Design*.Saxena, A. and Sahay, B. (2005), *Computer Aided Engineering Design*, Anamaya Publishers, New Delhi, India.
- Schuhmacher, G., Murra, I., Wang, L., Laxander, A., O'Leary, O. and Herold, M. (2002), "Multidisciplinary design optimization of a regional aircraft wing box", *AIAA paper*, vol. 5406.
- Sekulski, Z. (2010), "Multi-objective topology and size optimization of high-speed vehicle-passenger catamaran structure by genetic algorithm", *Marine Structures*, vol. 23, no. 4, pp. 405-433.

- Sobieski, I. (1993), "Multidisciplinary design optimization: attempt at definition", *Industry university workshop on multidisciplinary aircraft design*, pp. 23–48.
- Spillers, W. R. and MacBain, K. M. (2009), *Structural Optimization*, Springer.
- Van Tooren, M. and Krakers, L. (2007), "Multi-disciplinary design of aircraft fuselage structures", *45th AIAA Aerospace Sciences Meeting and Exhibit*, .
- Weigang, A. and Weiji, L. (2007), "Interactive Multi-objective Optimization Design for the Pylon Structure of an Airplane", *Chinese Journal of Aeronautics*, vol. 20, no. 6, pp. 524-528.
- Winer, E.H. and Bloebaum, C.L., (2002), *Development of visual design steering as an aid in large-scale multidisciplinary design optimization. Part I: method development*, Springer Berlin / Heidelberg.
- Yu, X. and Gen, M. (2010), *Introduction to Evolutionary Algorithms*, Springer London, London.
- Zander, J., & Sandström, R. (2012). Materials selection with several sizing variables taking environmental impact into account. *Materials & Design*, 37, 243-250.
- Zhou, M., Fleury, R., Shyy, Y. K., Thomas, H. and Brennan, J. (2002), "Progress in topology optimization with manufacturing constraints", *9 th AIAA/ISSMO Symposium and Exhibit on Multidisciplinary Analysis and Optimization*, Atlanta, GA, .
- Zitzler, E., Laumanns, M. and Bleuler, S. (2004), "A Tutorial on Evolutionary Multiobjective Optimization", in G. Bleich, X., Sevaux, M., et al (eds.) *Metaheuristics for Multiobjective Optimisation*, Springer, Berlin, pp. 3-37.
- Zitzler, E., Laumanns, M. and Bleuler, S. (2004), "A Tutorial on Evolutionary Multiobjective Optimization", vol. 535, pp. 3-37.
- Zhou, C. C., Yin, G. F., & Hu, X. B. (2009). Multi-objective optimization of material selection for sustainable products: artificial neural networks and genetic algorithm approach. *Materials & Design*, 30(4), 1209-1215.

APPENDICES

Appendix A Questionnaire

Structural Design Optimisation QUESTIONNAIRE

Name:		THIS PART IS OPTIONAL
Title:	Email:	
Company:	Date:	

INTRODUCTION

This questionnaire is part of Study of Optimisation Strategies for Aircraft Structural Design, an MSc by research project. It will take about 10 minutes to complete. It can be submitted by hand or through Email. A soft copy of this thesis could be sent to you on request.

Nowadays, engineers who want to optimise designs still need to spend a lot of time with learning and deciding on optimisation models, parameters, constraints etc. and how to combine simulation software best with the various optimisation algorithms. The work of engineers could become more efficient if they had practical guidelines that provided recommendations for a more systematic approach to optimisation of aerospace structures. This study addresses this general problem while focussing on applications of typical design tools such as CAD and FEA software.

The aim of this research project is to classify and summarize typical objectives and constraints in aircraft structural design optimisation, analyse and develop general workflows and approaches for various single, multi-objective and multi-disciplinary optimisation problems in this domain.

By completing this questionnaire you agree that this data can be used and processed for the legitimate purposes of this study in accordance with the requirements of the Data Protection Act 1998.

QUESTIONS

Please tick box which applies.

- 1) Which field do you work in?
☐ Aerospace ☐ Automobile ☐ Academic ☐ Other: _____
- 2) Which CAD software is used to design structures in your company?
☐ CATIA ☐ AutoCAD ☐ NX-UG ☐ None/Other: _____
- 3) Which FEA software is used to do structural analysis in your company?
☐ Hyperworks ☐ ABAQUS ☐ PATRAN ☐ None/Other: _____
- 4) Which software is used to do optimisation in your company?
☐ ModeFrontier ☐ iSight ☐ OptiStruct ☐ HEEDS ☐ ClearVu
☐ None/Other: _____



5) Some CAD or FEA tool has its own optimisation module, Do you use any of these module or why not?

6) What workflows (steps) do you set to carry out the optimisation?

7) How many input parameters are there in your optimisation?

☐ 1-2 ☐ 3-4 ☐ 5-6 ☐ More than 6

8) How many objectives are there in your optimisation?

☐ 1-2 ☐ 3-4 ☐ 5-6 ☐ More than 6

9) What are the typical objectives in your design and optimisation?

10) How many constraints are there in your optimisation?

☐ 1-2 ☐ 3-4 ☐ 5-6 ☐ More than 6

11) What are the typical constraints in your design and optimisation?

12) What are the most popular approaches for you to create DOE sequence?

☐ No idea ☐ Full Factorial ☐ Taguchi Orthogonal Arrays

☐ Central Composite Design ☐ Uniform Design ☐ Latin Hypercube

☐ Other: _____

13) What kinds of algorithm are commonly adopted in structural optimisation?

☐ No idea ☐ NSGA-II ☐ MOSA ☐ MOGT ☐ MOPSO ☐ FAST ☐ HYBRID

☐ SAnGeA ☐ Evolution Strategy ☐ DES ☐ Other: _____

14) How do you choose the algorithm to solve your problem?

15) What are the main difficulties and challenges in your structural optimisation?

16) Do you have any simple recommendations for novices that what to start an optimisation project?

17) What are you expecting from this study?

18) Do you think an easy to use guideline with practical recommendations on "How to define and solve structural design optimisation problems" would be useful for your work/company?

☐Yes ☐No

THANKS

Thank you for filling this questionnaire. Your help is much appreciated.

Huang Feng
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Lanbor1986@gmail.com



Appendix B Interview Outline

Structural Design Optimisation **INTERVIEW OUTLINE**

Name:		THIS PART IS OPTIONAL
Title:		Email:
Company:		Date:

GENERAL QUESTIONS

- 1) What is your first set of 5 questions you ask when you start an optimisation project?
- 2) What do you do if you do not have an explicit fitness function?
- 3) How many fitness evaluations are you typically allowed to use?
- 4) How do you shorten the time spent on the nonlinear convergence analysis in FEA?

5) How do you shorten the time spent on the evaluation of the fitness?

6) How to select the approach from evolutionary, classic and hybrid approaches?

7) How do you select the optimisation software?

8) Do you follow any best practice when you start optimising a problem?

SPECIFIC QUESTIONS

-
-
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-
-
-
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Appendix C Questionnaire Responses Excerpt

ID	What are the typical objectives in your design and optimisation?	What are the typical constraints in your design and optimisation?	How do you choose the algorithm to solve your problem?	What are the main difficulties and challenges in your structural optimisation?	What are you expecting from this study?	Some CAD or FEA tool has its own optimisation module, do you use any of these module or why not?	What workflows (steps) do you set to carry out the optimisation?	Any recommendations for novices?
R001	Weight	None	No idea	I have to spend a lot of time to study the software	A system of optimisation method	No, because its function is too simple	Catia- IGS MODEL- Hyperworks	It is better to learn Catia and Fea first
R002	Less weight, low stress, equalent stress. Easier manufacturing.	Geometry, material parameters, temperature, fixture requirement, deformation requirement, vibration requirement	Recommend by college	The optimised result always shows low manufacturing ability. Calculating effective is very low.	Can get an optimisation method considering manufacturing and fixture.	No, the optimised results always show mechanism result, but not manufacturing.	Initial shap, input load, changing details by less weight criteria.	No.
R003	Volume	cost time	No idea	It's difficult to indentify the load and constraints	a framework	too simple		master CFD or FEA

R004	most flowrate, least power	size	if one step computation take short time, robust method is chosen if one step computation take long time, fast method is chosen	set the workflow node and make them work correct	good lucky	The function is poor so that not use	the necessary node	make it easy to use
R005	Mass, compliance	stress, displacement, bolt force, strain, compliance	automatically chosen by software	getting a good start point to give a global optimum.	compare different optimisation techniques.	Yes, it's more efficient.	Model build - correlation- constraint setup- optimisation	Try to make it as simple as possible with no more elements than necessary to limit run time and resource requiremen ts.
R006	min mass, min- max (stress typically)	stress, displacements, compliance	leave it to the software	finding global minimum, run time, rationalising model size in terms of responses, variables of constraints.				

R007	topology/size/reliability/robust) 拓扑、尺寸、鲁棒性、可靠性等等	(Equality/inequality constraints, random statistics, Conditional Probabilities) 1、等式约束条件; 2、不等式约束条件; 3、随机统计、概率条件;	(modeFRONTIER integrated algorithm) modeFRONTIER标准算法	(Optimisation of the existing product or size)优化已有成熟产品或行业通用尺寸。	(Reliability robust optimisation)结构可靠稳健型优化	(lack of functions)没有足够的优化功能	(1.define the objective functions,2.define constraints, 3. Integration of different tools. 4. Choose the algorithm. 5 evaluate the result.)1、定义目标函数; 2、定义设计约束条件; 3、集成多学科软件; 4、选择优化算法; 5、评价优化结果。	(Read more about optimisation, and learn to develop the optimisation functions.)多看优化教材,对本学科专业软件操作熟练,懂一些2次开发。
R008	lift, drag, weight, costs	lift, drag, weight, costs	depending on the problem	time consuming evaluation	a list of best practises	yes, in Ansys	set the input, run some analysis, evaluate first results, and then optimise	reduce the problem as much as possible

R009	Minimise cost, CO2 emissions and maximise structural performance	Height, diameter and thickness	Computational time and application to specify problem	Writing the code for the optimisation problem	An optimised wind turbine tower in terms of cost, CO2 emissions and structural performance	Yes I use the optimisation toolboxes in Matlab	State Objective function, max or min problem, set constraints and parameters	Be as detailed as you can, define the objective functions, constraints, design variables, etc.
R010	temperature and flow coefficient	temperature and structure geometry	Multi-objective simulated annealing algorithm	Assembly stress (temperature)	it's interesting to see the applications in various of fields.	I used the optimisation module in FEA at the beginning, but it can't meet the requirements when I was trying to solve advanced engineering problems. So I use modefrontier instead, which has been proved to be very good.	Find the related case studies and reference from home and abroad to creat the workflow in modefrontier	Case studies are very important to learn from

R011	cost and weight	Based on the cost of the assembly and components		the FEA modelling and how to choose the algorithms.	Would like to know the future of the structural optimisation	No, few algorithms could be found in the ansys, and it takes a long time to optimise, what's worse, sometimes it comes out with a local optimum.	Mathematical model. First, determine the objective function, secondly, set up the variables, finally, set up the constraints.	simplify the mathematical model
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R012	displacement	Number of teeth Normal plane modulus The law face pressure angle Normal surface modification coefficient Helix angle	Sequential quadratic programming algorithm; Multi-objective particle swarm optimisation	the application of CAE in gear and Automatic meshing and Stress Analysis	The combination of CAD and CAE	Yes, I use optistruct, which is integrated with CAD- FEA- optimisation. But it's not good at DOE and Sensitivity analysis, and lacks of algorithms.	1. Geometry Modelling 2. FEA 3.Optimisation	Get full understanding of the engineering problem and read sufficient papers
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R013	<p>Performance - (minimising max strain/stress/temperature/force/flooding etc...) Cost - (mass/true cost)</p>	Anything	Based on no inputs, outputs and objectives + experience			<p>No.</p> <p>We use modeFRONTIER which is a generic tool and can be applied to all CAD/FEA packages.</p> <p>Individual optimisation modules tend to be limited in the algorithms available.</p> <p>modeFRONTIER can do process integration between different softwares and therefore perform multi-disciplinary optimisations</p> <p>mF can automate an entire development process from concept to manufacture</p>	Often there is a preprocessing script, a series of applications run and a post processing script	Attend an optimisation training course. Start with a simple workflow and build the complexity of the problem, don't jump to high complexity without knowing how to debug it.
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R014	Device performance	Size, frequency,	fair basic	objective function in math format	NA	Use Ansys and Matlab	normal academic methods	think real physics for optimisation
R015	Weight	stress	up to the software	hard to determine which variables are important	classify the existing optimisation problems so the engineer can take them into account rather than ignore them	No, it's not useful.	design a part as baseline to optimise using constraints.	find a tutorial to understand the procedure